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Review and Assessment of Deep-Well Injection of Hazardous Waste. Volume I

Louis R. Reeder and Associates, Tulsa, Okla

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Municipal Environmental Research Lab, Cincinnati, Ohio Solid and Hazardous Waste Research Div

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16. ABSTRACT

This four volume report is a review and assessment of the adequacy of deep-well waste injection systems to receive hazardous wastes and to define what effects that these wastes will have upon the environment when injected into subsurface reservoirs. All aspects of deep-well injection systems have been touched upon.

A comprehensive bibliography, chemical waste profiles, deep-well inventory, case histories, microbiological research, deep-well and hazardous waste research, legal aspects and an inventory of statues and regulations governing waste injection are discussed in the text and detailed in the appendices.

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Volume I

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic efforts of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This contract was supported by the EPA to provide a comprehensive review and data compilation of deep-well injection as a control and disposal technology for hazardous waste. Because of the large amount of information resulting from this contract, the report is divided into four volumes. Readers interested only in the general information about deep-wells are referred to Volume I. Those interested in the detailed data compiled during this work are referred to the remaining volumes in addition to Volume I. The information is providing input into the EPA's program for assessing control technologies available for managing the Nation's large quantities of hazardous materials.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

A review and analysis of the available information related to deep-well injection, and an assessment as to the adequacy of this method for managing hazardous wastes and ensuring protecting the environment was made.

One hundred-five deep-well related research projects were identified and hazardous waste research projects numbered 186. More than 1,000 papers related to deep-well injection of industrial waste were reviewed.

Geologic and engineering data are available in many areas to locate, design and operate a deep-well system receiving hazardous wastes. The most serious problems encountered are because of failure to use available geologic information and accepted and proven engineering practices in design and completion. A small group of waste chemicals with high human and ecological hazard ratings, little known degradability characteristics or long persistence times are identified as undesirable for injection unless containment within the host reservoir is certain.

There is a paucity of information on salaquifer chemistry, and the chemical and microbiological reactions of waste within a receiving salaquifer. Monitoring of deep-well systems needs to be developed into a predictive tool to be fully effective.

State statues and regulations vary greatly on deep-well injection. To alleviate any problems arising from the use of interstate aquifers for injection, and for more effective management and control of deep-well systems, a standardization of regulations is considered necessary.

This report was submitted in fulfillment of EPA Contract 68-03-2103. The report is comprised of 4 volumes; the main text, Appendices A through C, Appendix D, and Appendices E through J. This volume is the main text and is comprised of an executive summary and sections on the geologic, engineering, chemical, microbiological, and other aspects important in the environmental and technological evaluations of injecting hazardous waste into

deep-wells. Other volumes are appendices which are detailed compilations of data about deep-wells.

As a result of EPA review of this document, there were a number of questions and issues raised as to the conclusions made versus those warranted based upon available information. The user is referred to Appendix J for additional information resulting from this review and the contractors response to that review.

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SECTION 1

EXECUTIVE SUMMARY

The purpose of this report is to make an assessment of deep-well injection as a method to manage hazardous industrial wastes and ensure protection of the environment. Data were compiled from June to October 1974. Sources of information were existing literature, government agencies, individuals knowledgeable in deep-well techniques and industries using deep-wells as a waste management method. The review is intended to be as comprehensive as possible within the framework of available time and readily accessible material, and to show the strength and weakness of deep-well injection as an effective hazardous waste management tool.

ASSESSMENT

Geological

Enough geologic information is available in the United States to define areas in which deep-well injection is feasible and may be performed safely, areas where injection is possible but may produce detrimental effects to the environment, and areas where injection is either impossible, marginal, or will definitely have detrimental environmental effects.

Figure 1 found at the end of Section 1 is a physiographic map of the United States. The broad geomorphic regions used in this report have been outlined on it as have the EPA regions in order to show their geographic relationship. This figure is to be used for reference in conjunction with Tables 1, 2 and 3. Table 1, also found at the end of this section, is a summary of broad geomorphic areas of the contiguous United States and classifies them as to apparent geologic compatibility with deep-well injection and will, in most cases, serve to identify areas which may or may not be feasible for safe injection. Detailed investigation, however, must still be made for any given well site within an area rated as acceptable in the table.

The feasibility of a well site within an acceptable area may effectively be determined by using as reservoir guidelines the ten criteria of: 1) uniformity, 2) large areal extent, 3) substantial thickness, 4) high porosity and permeability, 5) low pressure 6) a salaquifer, 7) separation from fresh water horizons, 8) adequate overlying and underlying aquicludes, 9) no poorly plugged wells nearby and 10) compatibility between the mineralogy and fluids of the reservoir and the injected wastes. A reservoir so chosen will have the capability to contain safely, any waste that may be injected into it provided the injected volume does not exceed the available volume of the reservoir and injection pressures do not exceed critical formation pressures. These criteria for reservoir selection do not, however, preclude the integrity of the reservoir later being destroyed by operating improprieties or a force of nature such as earthquake rendering invalid the concept of containment and permitting fluid escape.

Engineering

Well design and construction, as of the date of this report, is adequate to handle safely the wastes now being injected and has the capability to handle any known wastes that may be added in the foreseeable future.

The design of a given system must be based upon the type reservoir, its transmissibility and storage capacity, the volume of waste to be injected, the rate at which it is to be injected, and the type of waste. No deep-well system can be designed and installed with the expectation of a successful operating life unless the effects of all the parameters related to the reservoir, the waste and the physical dimensions of the well are incorporated into the design.

Operating limitations must be established for every well to ensure that the limits of the equipment, the reservoir and the confining beds are not exceeded, and the waste released from the well bore or the host salaquifer.

Microbiological

Deep-well toxic waste injection has become one solution to the disposal of problem liquid wastes. Very little, however, has been done to examine the native flora of injection zone salaquifers. The effects of microorganisms on the injected wastes and injection zone salaquifers have not been determined except in a few studies. Seldom considered is the effect of microorganisms on the entire injection process from possible plugging effects of microbial growth to changes effected on the waste by microbial metabolic activities.

The studies which have considered microbial effects clearly show that the waste will be acted upon by microorganisms after it has been diluted by native aquifer water to conditions suitable for microbial metabolism. If the dilution and injection rates are carefully controlled, it may be possible to design microbial degradation of certain wastes in the injection aquifer. The transformations will vary according to the waste and biogeochemical reactions in the aquifer. The products of microbial action may be combinations of CO_2, H_2S, and CH_4.

The emergence of waste and/or products of the waste degradation may have effects on aquatic life in surface waters and may affect groundwater quality. What these effects may be are unknown at this time.

Viruses are known to survive outside the cells of their hosts, but nothing is known of their role in connection with waste injection. An in-depth study should be performed of the yeasts and viruses in subsurface waste injection.

Research is needed to provide a rational rather than an empirical basis for design and operation of deep-well toxic waste injection systems. Intensification of research, in which cooperative efforts of biologists, chemists, engineers, hydrologists, and geologists are needed, is required to ensure the continued safety of groundwater resources.

Chemical

A review of the chemicals contained in waste streams currently being injected into deep disposal wells was made to determine the potential hazards for deep-well injection. In performing the analysis, the toxicology, the degradability, the water solubility and the possible reactions were the main criteria considered. Some chemicals are highly toxic and possess other undesirable characteristics that make them unsafe for any system involving long-term storage. Other chemicals create problems because of their effect on the well systems. Acids can corrode certain types of casing or may react to dissolve the confining beds, also the grout sealing the pipe in the confining beds is subject to attack by some chemicals. Examples of the deterioration of well systems have been given in the sub-section on chemical aspects. The corrosion of the well materials and dissolution of the confining beds to allow leakage into shallower aquifers, or other usable mineral resources is one of the hazards of deep-well injection.

It must be emphasized that if waste is generated, there has to be a means of disposing of it and in some cases there may not be a safer method than deep-well injection. A waste, even of low toxicity would not be safe for injection if the injection well were not constructed in a way which would prevent leakage, and if a proper host zone were not selected. The reverse would also be true. If the well could be so constructed and the receiving salaquifer could be selected so that there could never be a possibility of escape, then it would be safe to inject any type of waste, regardless of how toxic or how hazardous it might be.

With especially hazardous materials which have long persistence periods, the long storage time necessary makes it more hazardous for these materials to be disposed of into deep-wells. Where extended storage time is necessary, the risk is increased due to the possibility of escape from the storage area through failure of the system or migration of the water. Because there is very little factual information concerning the persistence period of some compounds, or the reactions within an aquifer, this is an area where more research is needed.

The chemicals considered to be hazardous for deep-well injection in any system are:

acrolein

arsenic and arsenic compounds

cadmium and cadmium compounds

carbon disulfide

cyanides

diazinon and other pesticides

fluorides

hydrocyannic acid

hydrofluoric acid

hexavalent chromium compounds

mercury and mercury compounds

nitrobenzene

nitrophenol

All of the chemicals listed as hazardous for deep-well disposal have very high human and ecological hazard ratings in the Booz-Allen reports[1]. Long storage time is necessary for all of the listed organic chemicals. They either do not degrade or have a long persistence time and would, therefore, pose a long-term potential hazard to underground water supplies. The actual persistence time is not generally available except for a few rough estimates for a few pesticide compounds. Some of the pesticides with known long persistence time are: DDD, DDT, Lindane and the Polychlorocyclodienes. Dinitrocresol is one of the insecticides for which no persistence data is available. Chlordane, the organophosphorus insecticides and those listed above are among those not recommended for deep-well disposal by the National Working Group on Insecticides[2].

The inorganic compounds may react to form less toxic chemicals, but the toxic element or radical remains and may be converted back to the more toxic form, as in the case of hydrogen cyanide being converted to a salt, and then upon acidification being converted back to hydrogen cyanide. Arsenic and fluoride are lethal to all forms of life including plants. Cadmium and mercury are toxic to aquatic life. Mercury and organic mercury compounds may be converted by anaerobic microorganisms to the more toxic methyl mercury.

Detailed descriptions of the many chemicals being injected into deep-wells including the hazardous group identified in this section are shown in Section XI, Appendix C, Waste Characterization Profile Reports.

Of the 383 wells permitted, 209 were operating at the time the data were collected for this report. There were 53 of these operating wells injecting one or more of the chemicals deemed hazardous for deep-well disposal. Table 2 identifies the wells and the hazardous wastes being injected into them. Table 3 is a tabularized assessment of the operating deep-wells. Both tables are found at the end of this section.

The success of injecting less hazardous or relatively innocuous chemicals into deep-wells is dependent upon the formation, the fluids in the formation and the other chemicals in the waste streams. Because waste streams are a mixture of different chemicals, their activity will be affected by all the chemicals in the stream. If acidic waste is not neutralized before injection and is not injected into a zone containing sufficient carbonate to dissipate the acid, it may be transported out of the injection zone and into a zone containing usable mineral resources, unless the host zone is sealed above and below by beds impervious to acid. Other chemicals may react to form plugging materials which will damage the formation and prevent migration of waste away from the well bore. Some of the reactions which can cause plugging of the formation are listed in the chemical aspects subsection. Each waste stream should be evaluated to determine whether or not there is a better or safer method of disposal. If possible, some of the most hazardous chemicals and solids should be removed before injection if their removal and disposal can be done safely.

There have been cases reported of failures of systems to contain the injected waste in the selected reservoir. These failures can usually be avoided by proper evaluation of the waste, the formation, the fluids and the proper engineering of the well. Even when all precautions have been taken to ensure proper selection of sites and well constructed systems, hazards will still exist from accidents and unpredictable occurrences.

It is difficult to assess what impact the 13 chemicals or their compounds identified as hazardous for deep-well injection may have upon the environment. In their pure form and in high concentrations, the effect can be devastating. However, in low concentrations, mixed with other wastes and introduced into an underground environment of varying mineralogy and water chemistry, at highly varied pressures and temperatures, the reactions and effects upon the environment are unknown. The intraformational reaction shown in Table 3 is the initial stage in developing a reaction matrix for various waste streams that are being injected into subsurface reservoirs. Developed to its maximum potential, the reaction matrix could be a valuable tool in managing deep-well injection of hazardous waste by predetermining the reaction of a given mixture under almost any reservoir and injection conditions.

Brine

Brine injected into subsurface reservoirs and escaping can have a disasterous effect upon the flora and fauna of an area as well as contaminating fresh water aquifers. The surface effects can be temporary if the situation is not permitted to continue over an extended period. However, while the brine continues to escape, vegetation and aquatic life will be killed. Higher animals will seek fresher water and drink the brine contaminated water only as a last resort.

In many respects escaping brine contamination of fresh-water aquifers will have more lasting effects than brine escaping to the surface of the ground. Once contaminated, an aquifer is extremely difficult to purge, especially confined aquifers.

Sewage

Treated sewage is generally considered an innocuous fluid to inject into subsurface reservoirs. However, very little is known about the length of time some bacteria and viruses can remain alive and dormant outside a host. Therefore, sewage injected into deep-wells should be considered a latent potential health problem if it escapes from the receiving reservoir.

Monitoring

Monitoring is relatively effective in some areas of deep-well operation. When properly applied it is most effective in detecting equipment malfunction. At a specific point a monitor well may detect waste passage within a reservoir, but usually cannot confirm the escape of waste nor vertical fluid movement. After a waste stream is injected underground, there is practically no control over what happens to it or where it goes[7]. Intelligent use of monitor wells can often help detect adverse fluid movement and thereby early indication of damage and need for corrective measures. This offers a limit to potential hazards.

The active sampling and analyses of samples from monitor wells before, during and after the passage of a waste stream front could help in defining the complex state of equilibrium in natural water systems. Obviously, the state of equilibrium is an abstraction; natural waters are dynamic systems of variable mass on energy inputs and outputs. Hazards whether natural or created can be better handled as the knowledge of this area of the environment is expanded.

The inherent weakness of monitoring systems now in use is that the detection of problems and trouble in the systems is retrospective. To be fully effective, monitoring methods and techniques must be developed to identify the type and source of potential problems.

Legislation

The regulation of deep-well injection varies greatly between states in form, substance and administration. States with the largest number of deep-well installations usually have the most strict and comprehensive regulations governing the operation of the systems, but there are exceptions, e.g., Colorado. The lack of uniformity in permitting and operating requirements between states is one weakness that should be resolved to help develop good consistent management and control practices. This will give a consistency of data from the deep-wells operating throughout the country; a necessity in assessing the effect of hazardous waste injections upon the environment.

Legal

The four theories of tort law most likely to be applied in case of harm from deep-well injection of waste into subsurface reservoirs are: trespass, negligence, nuisance, and strict liability. The plaintiff's remedies are injunction and damages. The rule and remedy chosen by the plaintiff will be that most suitable to his case, easiest to prove and most likely to be sustained by the local court. Tralease indicates that the actor will have few defenses other than to attack the theory of the plaintiff for lack of an element in his case.

The new trend in law is toward "conditional fault" which will allow desirable conduct even though it has the possibility of harm. However, the actor will be required to pay if harm occurs.

It is not certain what the trend of the legal aspects of deep-well injection will be as no critical challenges have been made.

CONCLUSIONS

1. Sufficient geologic data are available to prepare comprehensive feasibility studies covering all geologic aspects except salaquifer hydrology.

2. Detailed information on the salaquifers throughout the U. S. is meager except in some localized areas where there has been extensive oil well drilling or subsurface brines have been exploited for their mineral content.

3. Careful consideration should be given to heavy brines to establish their mineral content for future use, e.g., iodine, bromine, before using the same reservoir to inject waste.

4. Brackish water up to 10 000 ppm TDS should be considered a potential resource and the long range effects considered before injecting any type waste into a reservoir containing less than 10 000 ppm TDS.

5. Adequate engineering data for design and completion of deep-well systems are available throughout the U. S.

6. The consensus of the personnel in industries using deep-well injection systems, and those contractors involved in the design and construction of the systems is that there has been adequate research related to deep-wells. They believe that the methods and techniques proven in water well drilling and completion, and oil well drilling and completion can be applied to deep-well systems safely, successfully, and can be economically feasible. Deep-well drilling and completion practices have followed this conclusion which also is supported by interviews, and the absence of privately funded research projects related to deep-well injection.

7. Deep-well injection systems for nearly all types of nonhazardous and hazardous industrial waste are a safe method of handling the waste if the systems are properly located, designed, operated, managed and regulated. Tentatively excluded as being safe for deep-well injection if containment is questionable are 13 chemicals and their related compounds identified in the Assessment section.

8. The planning and operation of a deep-well system is a multi-disciplinary effort involving geological, engineering, chemical, biological and legal expertise; none of which should be ignored.

9. Almost all deep-well operational failure can be attributed to failure to make use of available geologic information, ignoring these data when presented in a

feasibility report, or failure to follow proven engineering design and completion practices.

10. Weaknesses appear in limited areas in chemistry, microbiology, engineering, and geology in relation to deep-well injection.

11. The effects of escaping waste, or products of waste degradation on ground-water quality and aquatic life in surface waters is essentially unknown.

12. Reactions between waste, formation water, and formation minerals and the persistence period of compounds under varying conditions is not well understood. A better understanding of these reactions is essential if a good assessment of the overall effect of deep-well injection can be made.

13. Microbial degradation of some wastes in the receiving aquifer may be accomplished under controlled conditions.

14. The injected waste streams containing compounds with high human and ecological hazard ratings, and those whose persistence period and degradability pattern is little understood should be carefully monitored. Until these characteristics are better known alternate methods of disposal should be investigated in case any deep-well system is determined to be inadequate to handle safely any of the substances identified as hazardous for injection.

15. Brine entering aquifers containing potable water may destroy their usefulness. Brine leakage to the surface may destroy flora and fresh water aquatic life.

16. Sewage injected into the subsurface should be considered a latent health hazard until more is learned about the length of time some viruses and bacteria may remain alive and dormant outside a host.

17. Waste stream data on the inventories range from a very small number showing a fair amount of detail to the great majority with the waste stream listed in general or vague terms or not listed at all. Much of this information is considered proprietary information by individual companies and they will not release it. Many state regulatory agencies respect the companies regard for security on the analyses of the waste stream and will not release the information. This information is an essential factor in making an assessment of a deep-well installation.

18. Monitoring, in its present form, although adequate in detecting waste passage and equipment malfunction is ineffective for continuous tracking of waste movement within a reservoir, waste escape from a reservoir, or vertical movement of fluid.

19. Reservoir modeling in its present state-of-the-art is more a recording of historic data rather than a useful predictive tool. When a high degree of confidence in the predictive accuracy of the model can be developed to coincide with the early operating life of the well, it may develop into a useful tool for operating, management, and control of deep-well systems.

20. Too many persons involved in drafting regulations, permitting, and enforcing regulations relating to deep-well injection lack sufficient knowledge of well completions and the subsurface environment to qualify them for such decision making positions.

21. Most state regulations or policies have been adequate in the past. However, the policies and regulatory procedures used by the states are highly variable. Inasmuch as no general acceptance of deep-well injection as an environmentally sound procedure exists between states, between regulatory agencies, or between personnel within the same regulatory agency a consistency in approach should be adopted. Administrator's Decision Statement No. 5 and its recommended required evaluation data should serve as a guideline toward this end.

Local operating limitations or completion requirements exceeding the general rule must be determined for each geomorphic province within a state or region as each province will have unique problems.

22. The well inventory is incomplete on much of the physical well data. Generalized location data make well plotting and identification difficult. Both types of data are essential to make valid comments.

23. The state-of-the-art of deep-well injection may be adequately summarized by about ten selected papers from the mass of literature written about it thus far.

24. There has been much unnecessary redundancy in research projects relating to deep-well injection, and very little integration of these projects into an overall scheme with a goal of management and control of the injection systems and the injected wastes.

25. Much data relating to individual deep-well systems is not included in some state files or has not been delivered to the regulatory agency.

26. Many operational problems related to deep-well systems are neither discovered by regulatory and enforcement agencies nor reported by operators. This probably relates more to the wide variation in regulations on reporting rather than deliberate withholding of information.

RECOMMENDATIONS

1. Research of hazardous waste reaction with formation water and minerals under varying temperatures and pressures. Much of this information is now lacking but is essential in making a valid assessment of deep-well injection systems. Some initial studies have been made in this area of investigation by the Natural Resources Center of The University of Alabama.

2. Studies to identify persistence and degradation times for hazardous waste under varying reservoir conditions.

This is an area in which much information is needed and is essential in objectively assessing deep-well injection systems.

3. Studies on the reactions of waste streams from various industrial processes when mixed with those of other processes. This is of particular importance when two streams are injected into a common well or when two streams derived from different processes are being injected into a common host reservoir in close proximity to each other.

4. Studies to investigate the microbiological degradation of hazardous waste. This approach to the possible rapid degradation or neutralization of hazardous waste may alleviate many of the handling and disposal problems presently encountered.

5. Research to develop predictive or progressive monitoring methods. A breakthrough in this area will do much to answer many of the questions about fluid movement and reservoir integrity. It will be a very effective tool for management of subsurface waste injection.

6. A reaction matrix should be developed on the wastes now being injected. The initial stage of this was started with the intraformational reaction section of Table 3 of this report. The development of this matrix would not be definitive inasmuch as there are still many unknown factors that would necessarily be introduced in developing the matrix. Nevertheless it would establish what many waste salaquifer reactions would be and an assessment as to the environmental effect could be made with much more reliability than at the present time.

7. Data from salaquifers throughout the United States should be compiled to define areas suitable for injection and to be used in conjunction with waste and salaquifer reactions. Preliminary steps paralleling this were begun in 1971 in a program performed by the Bureau of Mines and sponsored by the EPA Office of Water Programs. This original program should be reviewed and developed.

8. Investigate to determine the length of time some bacteria or viruses might remain alive, but dormant outside a host in subsurface reservoirs.

9. Compile the material available on the effect of saline water on animals for use in determining the seriousness of brine contamination to subsurface potable aquifers and surface streams.

10. Keep the deep-well inventory updated on an annual schedule, and update and keep current the operating history of the wells. Periodic analyses of deep-well systems should be stated when enough critical data have been collected.

11. Standardized reporting procedures should be established for deep-well systems.

12. Use and no use areas, and horizons acceptable for injection should be established and clearly identified for each EPA region.

13. The injection of hazardous waste should be permitted to continue until there is positive evidence that it is having a deleterious effect upon the environment.

14. Special vigilance should be maintained in monitoring the wells into which one of the 13 chemicals or its related compound regarded as not recommended for deep-well injection is being injected. If there are any indications that the injected hazardous waste is escaping from the host reservoir, operations should be suspended immediately.

15. Alternate methods that are safe and economically feasible for treating hazardous wastes should be investigated for waste streams now being injected into subsurface reservoirs if: 1) the waste is shown to be escaping from the host zone, 2) the waste is having a detrimental effect upon the environment. Multiple alternative methods are shown in Appendix C of this report for most chemicals now being placed into deep wells.

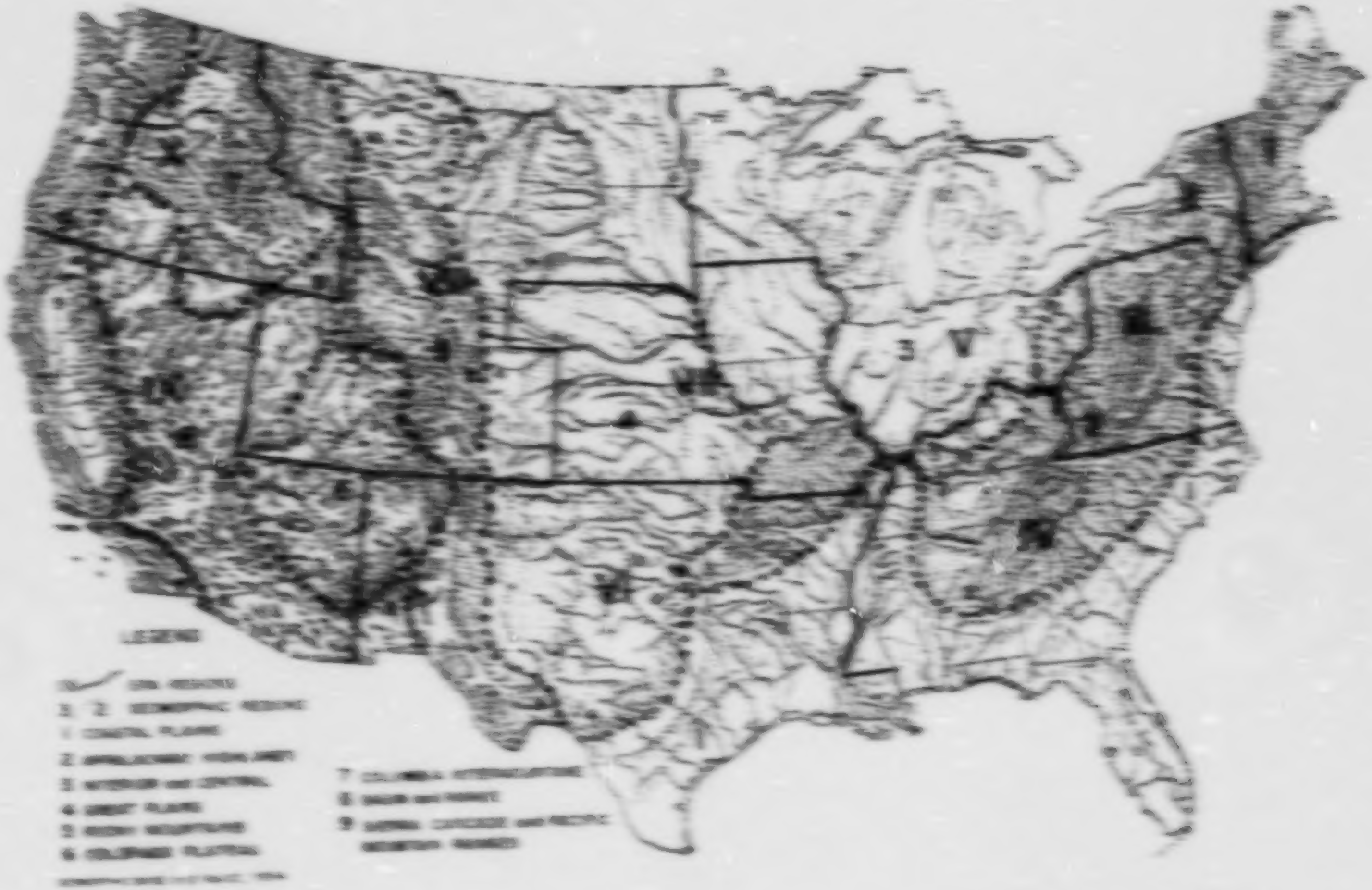
LEGEND
EPA REGIONS
3 2 GEOMORPHIC REGIONS
1 COASTAL PLAINS
2 APPALACHIAN HIGHLANDS
3 INTERIOR and CENTRAL
4 GREAT PLAINS
5 ROCKY MOUNTAINS
6 COLORADO PLATEAU
7 COLUMBIA INTERMONTANE
8 BASIN and RANGE
9 SIERRA, CASCADE and PACIFIC MOUNTAIN RANGES
[illegible]

Figure 1. Relationship of EPA regions to geomorphic regions in the United States, excluding Alaska & Hawaii.

Table 1. ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION IN ENVIRONMENTAL REGIONS

Areas	Reservoir Availability	Adequate Caleaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION I								
Connecticut	NR	–	–	–	–	1,2	X	
Maine	NR	–	–	–	–	2	X	
Massachusetts	NR	–	–	–	–	1,2,3	X	
New Hampshire	NR	–	–	–	–	2	X	
Rhode Island	NR	–	–	–	–	1,2	X	
Vermont	NR	–	–	–	–	2	X	
EPA REGION II								
New Jersey								
Cp	NR	–	–	–	–	1	X	
Pz	NR	–	–	–	–	1	X	
New York								
Pz/e	NR	–	–	–	–	1,2,3	X	
Pz/w	A	A	A	–	–		X-F	
EPA REGION III								
Delaware	NR	–	–	–	–	1	X	
Maryland	NR	–	–	–	–	1,2		
Pennsylvania								
Pz/e	NR	–	–	–	Yes	1	X	
Pz/w	A	A	A	–	Yes	1,2	X	

Table 1 (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIME

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION III (continued)								
Virginia								
Cp	LA	–	–	Yes	–	1	X	
Pd	NA	–	–	–	Yes	2	X	
Washington D.C.	NA	–	–	–	–	2	X	
West Virginia								
Ap/e	NA	–	–	Yes	Yes	1,2	X	
Ap/w	A	A	A	–	Yes	1	P-F	
EPA REGION IV								
Alabama								
Cp	A	A	A	300m (1000')	Yes	0	P-G	
Ap/e	NA	NA	–	150m (500')	Yes	1,2	X	
Ap/w	LA	LA	A	150m (500')	Yes	1,2	P-F	
Florida								
Cp	A	A	LA	300m (1000')	Yes	0,1	P-F	
Georgia								
Cp	A	LA	LA	300m (1000')		1,3	X	
Pd	NA	NA	–	–	Yes	2	X	

Table I (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIMES

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION IV (continued)								
Kentucky								
Ap	NA	NR	–	300m (1000")	Yes	1,2	X	
IL	LA	LA	A	< 150m (500")	Yes	1,2	X-P	
Cp	A	NR	A	150m (1000")	Yes	3	X	
Mississippi								
Cp	A	A	A	> 300m (1000")	Yes	0,3	X-P	
North Carolina								
Cp	A	LA	LA	150m (500")	–	1	X	
Pd	NA	NR	–	–	Yes	2	X	
South Carolina								
Cp	A	LA	LA	300m (1000")	–	3	X	
Pd	NA	NR	–	–	–	2	X	
Tennessee								
Cp	A	LA	LA	> 300m (1000")	Yes	2,3	X	
Ap/e	NA	NR	–	–	Yes	1,2	X	
IL/w	A	LA	LA	< 150m (500")	Yes	1,2	X-P	

Table 1 (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIONS

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION V								
Illinois								
IC	A	A	A	< 150m (500')	Yes	1,3	B-G	Injection limited to salaquifers of 10,000 ppm TDS or more.
Indiana								
IC	A	A	A	< 150m (500')	Yes	1,3	B-F	
Michigan								
IC/b	A	A	A	> 300m (1000')	Yes	1	B-G	
IC/a	NA	NA	-	-	Yes	1	X	
Minnesota								
IC	IA	IA	IA	To Basement	Yes	1	X	
Ohio								
AB	A	A	A	< 150m (500')	Yes	1	B-F	
IC	A	A	A	< 150m (500')	Yes	1,2	B-F	Injection limited to Mt. Simon Sandstone
Wisconsin	IA	IA	IA	To Basement				

Table 1 (Continued). SUITABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGION

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION VI								
Arkansas								
Cz	A	LA	A	> 300m (1000')	Yes	1,3	E-F	
Pz	LA	LA	LA	To Basement	Yes	1	E-F	
Louisiana								
Cz	A	A	A	> 300m (1000')	Yes	1	E-G	
New Mexico								
Cz	A	A	A	< 150m (500')	Yes	1	E-F	
P	NA	NA	NA	< 150m (500')	Yes	1,2	X	Excluding inter-montane basins
M	LA	LA	LA	< 150m (500')	Yes	2	E-F	
Pz	LA	LA	LA	Variable	Yes	2	E-F	
Oklahoma								
Pz	LA	LA	LA	< 150m (500')	Yes	1	E-F	
Cz	A	A	A	< 150m (500')	Yes	1,2	E-F	
Texas								
Cz	A	A	A	300m (1000')	Yes	0,1	E-G	

Table 1 (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION IN ENVIRONMENTAL REGIME

Areas	Reservoir Availability	Adequate Aquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION VI (continued)								
Texas								
Gp	A	A	A	< 150m (500')	Yes	1,2	H-F	
EPA REGION VII								
Iowa								
IC	A	IA	A	150m (500')	-	1	H-F	
Kansas								
Gp	A	A	A	> 150m (500')	Yes	1,2	H-F	
Missouri								
IC	A	IA	IA	To Basement	Yes	1,3	H-F	Injection prohibited by State regulations
Nebraska								
Gp	A	A	A	> 300m (1000')	Yes	1,2	H-F	
EPA REGION VIII								
Colorado								
Gp	A	A	A	> 150m (500')	Yes	1	H-F	

Table 1 (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIME

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION VIII (continued)								
Colorado:								
R	NA	NA	NA	300m (1000')	Yes	1	X	Excluding inter-montane basins
I	LA	LA	LA	150m (500')	Yes	1	X-F	
Montana								
Gp	A	A	A	< 150m (500')	Yes	1	X-F	
R	NA	NA	NA	< 150m (500')	Yes	1,2	X	Excluding inter-montane basins
Cl	LA	LA	?	Deep	Yes	2,3	X	
North Dakota								
Gp	A	A	A	< 150m (500')	Yes	1	X-F	
South Dakota								
Gp	A	LA	A	300m (1000')	Yes	1	X-F	
Utah:								
B	NA	NA	NA	Variable	Yes	1,2	X	
R	LA	LA	LA	< 150m (500')	Yes	2,3	X-F	
Cp	LA	LA	LA	< 150m (500')	Yes	2,3	X-F	

Table 1 (continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIME

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION VIII (continued)								
Wyoming								
Gp	A	A	A	> 150m (500')	Yes	1	B-F	
R	NA	NA	NA	300m (1000')	Yes	1,3	X	Excluding inter-montane basins
EPA REGION IX								
Arizona								
K	LA	LA	LA	300m (1000')	Yes	2	B-F	
Br	LA	LA	LA	< 150m (500')	Yes	2	B-F	
California								
S	LA	LA	LP	< 150m (500')	Yes	2,3	B-F	Injection in the Great Valley B-F
Hawaii								
Vu	A	A	NA?	Variable	-	2,3	B-F	
Nevada								
Br	LA	LA	LA	< 150m (500')	-	2,3	B-F	

Table 1 (Continued). ACCEPTABILITY OF DEEP-WELL INDUSTRIAL WASTE INJECTION TO ENVIRONMENTAL REGIMES

Areas	Reservoir Availability	Adequate Salaquifer	Adequate Aquiclude	Main Fresh Water Aquifers to Penetrate	Mineral Resources	Seismic Risk	Rating	Remarks
EPA REGION X*								
Idaho:								
Br	[illegible]	[illegible]	[illegible]	< 150m (500')	Yes	1	X	
Cl	[illegible]	[illegible]	?	Variable	Yes	2	X	
Oregon:								
S	[illegible]	[illegible]	[illegible]	< 150m (500')	Yes	1,2	[illegible]	
Br	[illegible]	[illegible]	[illegible]	< 150m (500')	Yes	1,2	[illegible]	
Cl	[illegible]	[illegible]	?	Variable	Yes	1,2	X	
Washington:								
Cl	[illegible]	[illegible]	?	Variable	?	2	X	
S	[illegible]	[illegible]	[illegible]	< 150m (500')	?	2,3	X	

*Alaska not covered.

Code Used in Table 1

RESERVOIR AVAILABILITY

LA = Availability Limited

A = Available

NA = Not Available

AREA ACCEPTABILITY

X = Unacceptable

P = Poor

F = Fair

G = Good

E = Excellent

GEOMORPHIC REGION

Cp = Coastal Plains

Ah = Appalachian Highlands

IC = Interior and Central

Gp = Great Plains

R = Rocky Mountains

K = Colorado Plateau

Ci = Columbia Intermontane

Br = Basin and Range

Va = Volcanic and Atoll

SEISMIC RISK

0 = None

1 = Minor

2 = Moderate

3 = Major

[illegible]

	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]														
[illegible]														
[illegible]														
[illegible]														
[illegible]		[illegible]						[illegible]			[illegible]			[illegible]
[illegible]														
[illegible]							[illegible]							
[illegible]								[illegible]						
[illegible]														
[illegible]														
[illegible]														
[illegible]														[illegible]
[illegible]														
[illegible]							[illegible]	[illegible]		[illegible]				
[illegible]						[illegible]				[illegible]				
[illegible]						[illegible]	[illegible]							
[illegible]						[illegible]								
[illegible]														
[illegible]														
[illegible]	[illegible]			[illegible]		[illegible]				[illegible]		[illegible]	[illegible]	
[illegible]														
[illegible]										[illegible]				
[illegible]	[illegible]	[illegible]				[illegible]			[illegible]	[illegible]				
[illegible]														
[illegible]														
[illegible]										[illegible]				
[illegible]														
[illegible]														
[illegible]														
[illegible]														
[illegible]														
[illegible]														
[illegible]														

[illegible]

Table 3. [illegible]

Region and No.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Remarks
[illegible]																	[illegible]
[illegible]																	
[illegible]		X				–	–	–	–	–	–	X	–	–	–	X	
[illegible]																	
[illegible]																	
[illegible]		X				X	–	–	–	–	–	X	X	–	[illegible]	X	[illegible]
[illegible]		X				[illegible]	–	–	–	–	–	X	[illegible]	–	[illegible]	X	
[illegible]				X		X	–	–	–	–	–	X	[illegible]	–	[illegible]	X	
[illegible]			X			–						X	X		[illegible]	X	
[illegible]				X								X	X		[illegible]	X	[illegible]
[illegible]		X											X		[illegible]	[illegible]	
[illegible]																	
[illegible]				X							X	X	[illegible]	X	[illegible]	[illegible]	
[illegible]				X								X	X	X	[illegible]	[illegible]	
[illegible]			X						X	X		X			[illegible]	[illegible]	[illegible]
[illegible]			X	X					[illegible]	X		X			[illegible]	[illegible]	[illegible]
[illegible]			X	X				X		X		X			[illegible]	[illegible]	
[illegible]												X	X		[illegible]	[illegible]	[illegible]
[illegible]			X	X								X			[illegible]	[illegible]	
[illegible]			X	X								X			[illegible]	[illegible]	
[illegible]	X											X	[illegible]		[illegible]	[illegible]	[illegible]
[illegible]															[illegible]		[illegible]
[illegible]			X	X	[illegible]								X		[illegible]	X	
[illegible]		X										X	X		[illegible]	X	[illegible]
[illegible]																	
[illegible]			X	X							X	X	X	X	[illegible]	X	
[illegible]		X										X	X	X	[illegible]	X	[illegible]
[illegible]			X	X							X	X	X	X	[illegible]	X	
[illegible]				X							X	X	X	X	[illegible]	X	

Table 7 continued. ASSESSMENT OF EXISTING DEEP-WELL [illegible] WASTE [illegible]

Region and well	[illegible]: Undetermined	[illegible]: Not unfavorable	Unfavorable: Old	Unfavorable: Poor	Unfavorable: Other	Approach critical pressure	Insufficient aquitards	Suspected fresh water contamination	Penetration interface affected	Reservoir water under 10,000 ppm	Abandoned wells near	Monitor wells	Other monitors	Minerals in area	Seismic risk	Saline	Remarks
Region [illegible] (continued)																	
[illegible]		x										x	x		1	x	
[illegible]		x										x	x		1	x	
[illegible]		x										x	x		1	x	
[illegible]		x									x	x	?	x	1	x	1227' confining bed
[illegible]		x										x	x		1	x	
[illegible]		x										x	x		1	x	
[illegible]		x										x	?		1	x	
[illegible]		x										x	?		1	x	
[illegible]		x										x	x		1	x	[illegible] 460 psi., [illegible] > 0.9
[illegible]		x		x		x				10,000		x	x		1	?	[illegible] over 460 psi.
[illegible]		x		x		x				10,000		x	x		1	?	[illegible] > 0.9
[illegible]		x								x		x	?		1	x*	*Life of [illegible] in effluent [illegible]
[illegible]	x											x	?		1	x	
[illegible]	x											x	?		1	x	
[illegible]	x											x	?		1	x	
[illegible]	x											x	?		1	x	
[illegible]	x										x	x	x	x	1	x*	[illegible] operation < 100 ppm
[illegible]		x		x		x				10,000		x	?		1	?	[illegible] 460 psi. [illegible]
[illegible]	x											x	?		1	x	Little information
[illegible]	x														1	?	Little information
[illegible]	x											x	?		1	x	
[illegible]	x											x	?		1	x	
[illegible]	x											x	x		1	x	
[illegible]	x											x	?		1	x	Information lacking
[illegible]	x											x	x		1	x	*Information lacking
[illegible]		x								4,750		x		x	1	x*	*Because of 4,000 ppm in test zone
[illegible]				x													
[illegible]	x										x	x	x	x	[illegible]	?	
[illegible]				x		x					x	x	?		1	?	
[illegible]		x										x	?		1	?	
[illegible]		x									?	x		x	1	?	
[illegible]			x	x								?	x	x	1	?	

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]																	
[illegible]			[illegible]								[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]				[illegible]					[illegible]	[illegible]			[illegible]	[illegible]	
[illegible]				[illegible]		[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
[illegible]	[illegible]										[illegible]			[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]		[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]									[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]			[illegible]	[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				[illegible]		[illegible]					[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]							[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]				[illegible]							[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				[illegible]							[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	
[illegible]		[illegible]									[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 3 (continued). [illegible]

	Undetermined	Not Unfavorable	Unfavorable Yes	Unfavorable Prob.	Unfavorable Other	Approach critical pressure	Insufficient Aquitude	Suspected Fresh Water Contamination	Fresh-Saline Interface Affected	Reservoir Water Under 10,000 ppm	Abandoned Wells Near	Monitor Wells	Other Monitors	Minerals in Area	Seismic Risk	Rating	Remarks
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]
[illegible]	No operating wells
[illegible]	Brine

[illegible]

TABLE 7 (CONTINUED). ASSESSMENT OF OPERATING DEEP-WELL INJECTION HAZARDOUS WASTE

Region and Well	Confinement of Injection: Undetermined	Not Unfavorable	Unfavorable: Lit.	Perm.	Other	Aquifers Critical Utilized	Insufficient Aquitards	Suspected Fresh Water Contamination	Fresh-Saline Interface Affected	Reservoir Water Under 10,000 ppm	Abandoned Wells Near	Monitor Wells	Other Monitors	Minerals in Area	Seismic Risk	Rating	Remarks
Region VIII																	
CO																	No operating wells
WY-1				X							X	X	X	X	[illegible]	[illegible]	
Region IX																	
CA-1				X								X			[illegible]	[illegible]	
CA-2				X								X			[illegible]	[illegible]	
CA-4				X								X			[illegible]	[illegible]	
CA-5		X									X	X		X	[illegible]	[illegible]	
HI-1		X													[illegible]	[illegible]	Monitor virus and bacteria
NV-1				X								X	X	X	[illegible]	[illegible]	Monitor [illegible] pH and [illegible]

Code Used in Table 2.

States & Wells

States - Identified by standard two
(2) letter abbreviation.
Wells - Identified by sequence appearing
in Inventory. (Appendix D).

Seismic Risk

Possible Damage:
0 - None
1 - Minor
2 - Moderate
3 - Major

Remarks

T - Toxic or Hazardous Wastes Injected
IOACP - Injection Often Approaches
Critical Pressure
FPR - Fracture Pressure Reached

Letter Code for:
All Columns Except
Seismic Risk & Rating

Y - Yes or present
N - No or not known
* - Refer to Remarks column

Well Rating

A - Acceptable
L - Limited acceptability
M - Marginal
U - Unsatisfactory

All Columns

? - Questionable or
information lacking

SECTION I

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SECTION II

INTRODUCTION

Injecting liquid industrial waste into underground formations is often an economical, attractive, but not necessarily practical or safe means for disposing of these wastes. Waste management and the control of water and air pollution are becoming increasingly difficult and more complex. The unprecedented population and industrial expansion and concentration, the revolutionary new technologies, and changing land uses and practices have presented enormous pollution problems to be solved by a relatively unprepared science. Research must now be concerned with new problems caused by the sheer mass of pollutants and by whole groups of new pollutants that are highly complex in composition, and which may persist for extremely long periods, and possibly indefinitely when in solution.[1,2]

With this formidable task of sensible and practical waste management now presented to industry, science, and government agencies, the strength and weaknesses of known systems must be examined and their value to the scheme of waste management established.

PURPOSE OF THIS REPORT

The purpose of this report is to make an assessment of the adequacy of deep-well injection as a method to manage the hazardous industrial waste in a manner that will insure protection of the environment from adverse effects.

SCOPE OF THIS REPORT

This report is to present as comprehensive an assessment of hazardous waste management by deep-well injection as can be permitted by the controlling factors of time, permissible contacts, and budget limitations.

The information base is to be established with available literature. This information base is supplemented by personal contacts with individuals, industry, and government agencies concerned with deep-well injection and having expertise in this field. The report covers the geologic, engineering, chemical, and biological aspects of deep-well injection of industrial waste.

An analysis of the data collected from the various sources synthesized an assessment of the environmental effects of disposal of hazardous waste into deep-wells, and contains recommendations for research and development and other activities required by the EPA to assess the effectiveness of deep-well injection as an available technique for the management of hazardous waste.

Data supplemental to the assessment sections of the report include injection well inventory, profile reports on hazardous waste being injected into deep-wells, and inventory of legislation of various states throughout the United States, summaries of research projects, past and present, and a cross referenced comprehensive bibliography of available literature on the subject of deep-well injection.

DEEP-WELL INJECTION

The prefix deep when applied to the phrase "deep-well injection" is often confusing. This prefix does not refer to any specific depth nor to the soil cover, but refers to rock formations which,are below and isolated from fresh water aquifers. Galley defines the term to mean rock formation, not soil, which lie below and are isolated from fresh water aquifers so that injected liquids will not enter potential water supplies or mineral resources either by natural means or by any process that is induced by the injection. Galley indicates that this usage calls for permeable rock layers several hundred meters deep, generally 900 metres (3000') in geologic basins confined above by thick relatively impermeable and fracture resistant strata such as shale or salt deposits. These criteria expressed by Galley have not always been adhered to, often with undesirable results and at least temporarily degrading effects upon the environment. The minimum depth of burial, the necessary thickness of confining strata, and the minimum salinity of water in the injection zone have not been established quantitatively, and it may be possible to specify these constraining parameters only for individual cases, as has been done in the past.

In most cases the minimum depth of burial can be considered to be that depth at which a confining saline-water-bearing zone is present; it may range from a few hundred to several thousand feet. The minimum salinity of water in the injection zone is generally specified by the regulatory agencies in most states, and will vary from at least 1 000 mg/l of dissolved solids to 10 000 mg/l total dissolved solids.

Concept

The concept of underground injection of liquid wastes was developed by the oil industry early in its history, when surface drainage was becoming contaminated by oilfield brines. The operators developed the now-common practice of injecting salt water wastes back into the subsurface reservoirs from which the oil and salt water originally were produced, and also into shallower or deeper reservoirs which had the storage capacity to accept the injected brine. This practice was not long established when it became obvious that the injected brines were contaminating fresh water sands that were being used for domestic supplies. This disposal practice for oilfield brines matured, and under the control of state laws has become a standard and accepted practice. More recently numerous other industries have turned to deep-well injections as a possible solution for their chronic waste disposal problem.[7,8,9] About 1958, the AEC began serious consideration of this method as a possible means for disposing of certain types of radioactive waste liquids.

The concept was developed to the degree that in 1974 in addition to over 40 000 oilfield brine disposal wells[6,7,8] there are 209 operating industrial waste disposal wells in the United States, as well as approximately five to eight thousand sewage and storm water disposal wells in the states of Oregon and Idaho. In addition to these wells in the United States there are an estimated 20 wells operating in Canada and two or three wells operating in Mexico.

Philosophy

The governing philosophy of the concept of deep-well injection of industrial waste is to dispose of a maximum amount of hard-to-treat, toxic, hazardous, or innocuous waste at a minimum cost, with the least deleterious effect upon the environmental regime of which the well is a part.

BACKGROUND OF DEEP-WELL EXPERIENCE

These historical data presented are the compilation of inventories by Donaldson[6], Warner[7,8,9], Ives, and Eddie for the Interstate Oil Compact Commission[10,11], WAPORA[12], and the files of various state regulatory agencies. The tables and figures shown with these data have been updated to January 1975, unless noted otherwise.

The present inventory shows at least 383 deep-well injection sites for which permits had been granted, located in 25 states. Wells were drilled on 322 of the sites, and 209 were being used for waste injection in 1974. Figure 2 shows the growth of operating injection wells in the U. S. by year. The rapid development of industrial waste

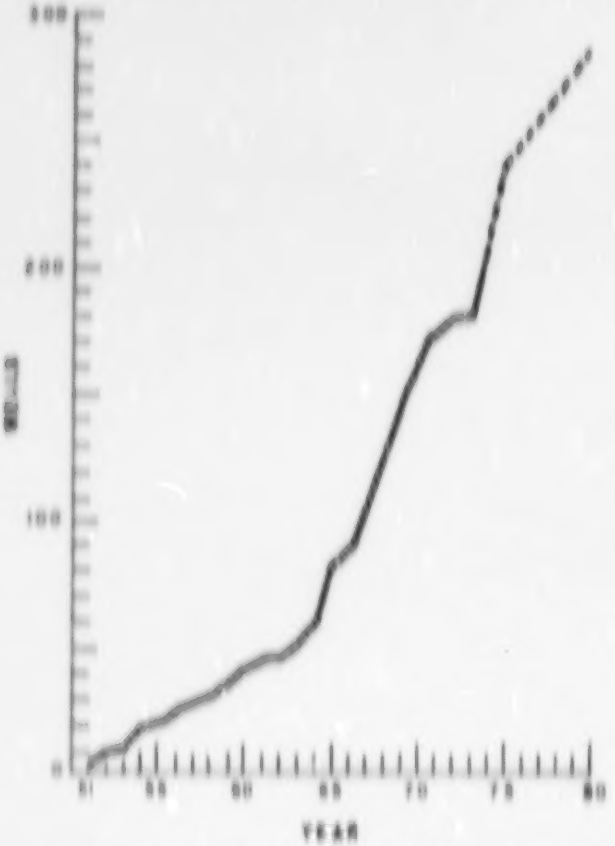

Figure 2. Growth of operating deep-well injection systems in the United States.

injection wells as indicated by Figure 2 is of concern to the federal, state, and local governments because of the many uncertainties related to deep-well injection which relate directly to the degradation of the environment.

Tables 4, 5, and 6 indicate the standard industrial classification of injection wells, rock type and age of host reservoirs and well completion depths, respectively.[17]

Table 4. STANDARD INDUSTRIAL CLASSIFICATION
OF INJECTION WELLS
(268 Wells)

	WELLS	PERCENTAGE
MINING (9.3%)		
10 Metal Mining	2	.7
12 Coal	1	.4
13 Oil & Gas Extraction	17	6.4
14 Non-Metallic Mining	5	1.9
MANUFACTURING (80.6%)		
20 Food	6	2.2
26 Paper	3	1.1
28 Chemical & Allied Products	131	48.9
29 Petroleum Refining	51	19.0
32 Stone & Concrete	1	.4
33 Primary Metals	16	5.9
34 Fabricated Metals	3	1.1
35 Machinery - Except Electronics	1	.4
38 Photographics	3	1.1
TRANSPORTATION, GAS, AND SANITARY SERVICES (9.8%)		
47 Transportation Service	1	.4
49 Sanitary Service	23	8.6
50 Wholesale Trade - Durable	1	.4
55 Auto Dealers & Service	1	.4
OTHER (.4%)		
72 Personal Service	1	.4

Table 5. RESERVOIR ROCK TYPE AND AGE (269 WELLS)

	(%)	SAND & SANDSTONE	CARBONATE	EVAPORITE	SHALE	OTHER
TERTIARY	39.4	93	11	2		
CRETACEOUS		19				
JURASSIC	7.4					
TRIASSIC		1				
PERMIAN		12	14	2		
PENNSYLVANIAN		5	2			
MISSISSIPPIAN		4	1			
DEVONIAN	53.2	10	21		1	
SILURIAN		1	3	4		
ORDOVICIAN		2	20			
CAMBRIAN		20	19		1	
PRECAMBRIAN	.4					1
TOTAL (269)		167	91	8	2	1
%		62.1	33.8	3	.7	.4

Overall the injection of industrial liquid waste into the subsurface reservoirs has been acceptable. To this overall smoothly operating scheme, there have been notable exceptions among which can be included the Rocky Mountain Arsenal well at Denver, Colorado, the Hammermill Paper Company well at Erie, Pennsylvania, and the Hercules Company well at Wilmington, North Carolina. Many cases, both good and bad, are discussed in the section on case histories and in other sections directly related to the geologic, engineering, chemical, or biological aspects of deep-well disposal.

In all cases studied, it was determined that major failures of injection systems could be directly related to two basic factors. The first is that the geology of the area was not studied thoroughly prior to drilling the well, or if studied the result of the studies were ignored or slighted in the planning. The second factor is that poor engineering design was employed, or poor well completion practices were followed. Chemical and biological factors also have contributed to well failures, however, unlike the geologic and engineering factors, the chemical and biologic factors are often correctable if they are not allowed to progress too far.

Table 6. WELL COMPLETION DEPTHS (262 WELLS)

DEPTH	NO. WELLS	PERCENTAGE
0 - 1000	20	7.6
1001 - 2000	56	21.4
2001 - 3000	33	12.6
3001 - 4000	34	12.8
4001 - 5000	39	14.8
5001 - 6000	44	16.7
6001 - 7000	18	7.2
7001 - 8000	12	4.8
8001 +	3	1.2

SECTION II

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SECTION III

DEEP-WELL INJECTION OF HAZARDOUS INDUSTRIAL WASTES

The ultimate and highly desirable end of industrial waste would be recycling or conversion of the waste into some usable product. However, at the present time there are large volumes of waste which are either indestructible or cannot be converted economically. Wastes of these types are the ones that should be considered prime material for controlling deep-well injection and storage, if the deep-well method is proved safe and acceptable to receive them.

GEOLOGIC ASPECTS

The general geologic characteristics that establish the suitability of areas for deep-well injection can be outlined. More detailed studies are necessary to show depth, distribution and physical characteristics of specific potential injection zones within the areas considered generally suitable. Suitable disposal zones are those with proper injectivity and storage capacity characteristics. Experience in the oil industry has shown that nearly all types of rocks may, under favorable circumstances, have sufficient porosity and permeability to yield or accept large amounts of fluid. Sedimentary rocks, especially those deposited in a marine environment, are the most likely to have the geologic characteristics suitable for waste injection wells. Detailed geologic and engineering studies of local areas having the characteristics required for these potential injection zones are necessary before a recommendation can be made regarding site suitability. Figure 3 indicates the general areal suitability for deep-well injection of industrial waste in the United States. When interpreting this figure it must be realized that it outlines the defined areas only in the broadest sense. Those areas designated as unfavorable or having limited or restricted use are conservative, and generally well established. The areas shown as favorable indicate the probable presence of a reservoir and adequate aquiclude and require detailed investigation for each proposed site.

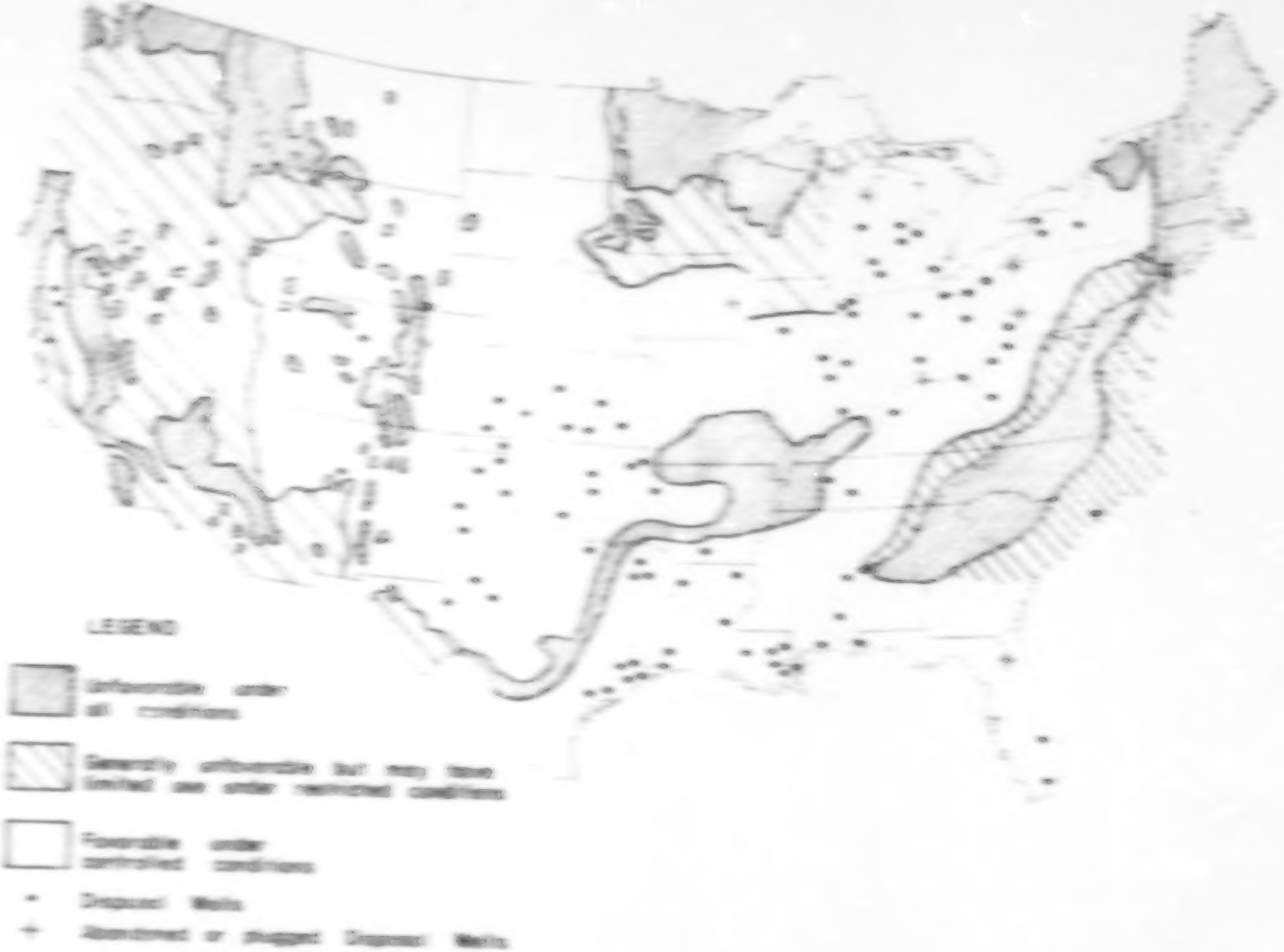
LEGEND
Unfavorable under all conditions
Generally unfavorable but may have limited use under restricted conditions
Favorable under controlled conditions
Disposal Wells
Abandoned or plugged Disposal Wells

Figure 3. Site suitability for deep-well injection of industrial waste

These areas contain many local areas unsuitable for the injection of waste of any type. The feasibility of injecting hazardous waste into any given reservoir at any locality must be determined by a detailed study of the local areas.

Geologically Acceptable Areas

Warner[1] indicated that the major synclinal basins are accepted as geologically favorable sites for deep-well injection, and that other areas may be generally unfavorable because sedimentary rock cover is thin or absent. This statement, although generally acceptable, necessarily must be qualified because of the numerous variables which must be weighed in considering a site for deep-well injection.

The many areas where relatively impermeable igneous and metamorphic rocks crop out are shown in Figure 4[2]. These areas generally can be eliminated from consideration for waste injection. Positive areas of igneous and metamorphic rocks outside the major mountain ranges are significant factors in locating waste injection wells, although, they may not be areally extensive. The outcrop and recharge area of the overlying sedimentary sequence often ring the flanks of such features resulting in unconfined fresh water aquifer for great distances down dip precluding the injection of wastes into the reservoir rocks without contamination.

Those areas of Figure 4 in the northwestern United States where a thick volcanic sequence is present at the surface generally are not acceptable as waste-injection well sites. Although these volcanic rocks have fractures, fissures, and intercalated gravel beds that will accept the injected fluids, they contain fresh water, often to great depths, which at some point probably will be in communication with the injected fluid.

The immense and geologically complex Basin and Range province of the southwestern United States is a series of narrow basins and intervening structurally positive ranges. Many of the basins might provide waste-injection sites, but their geology is generally unknown and the cost of obtaining

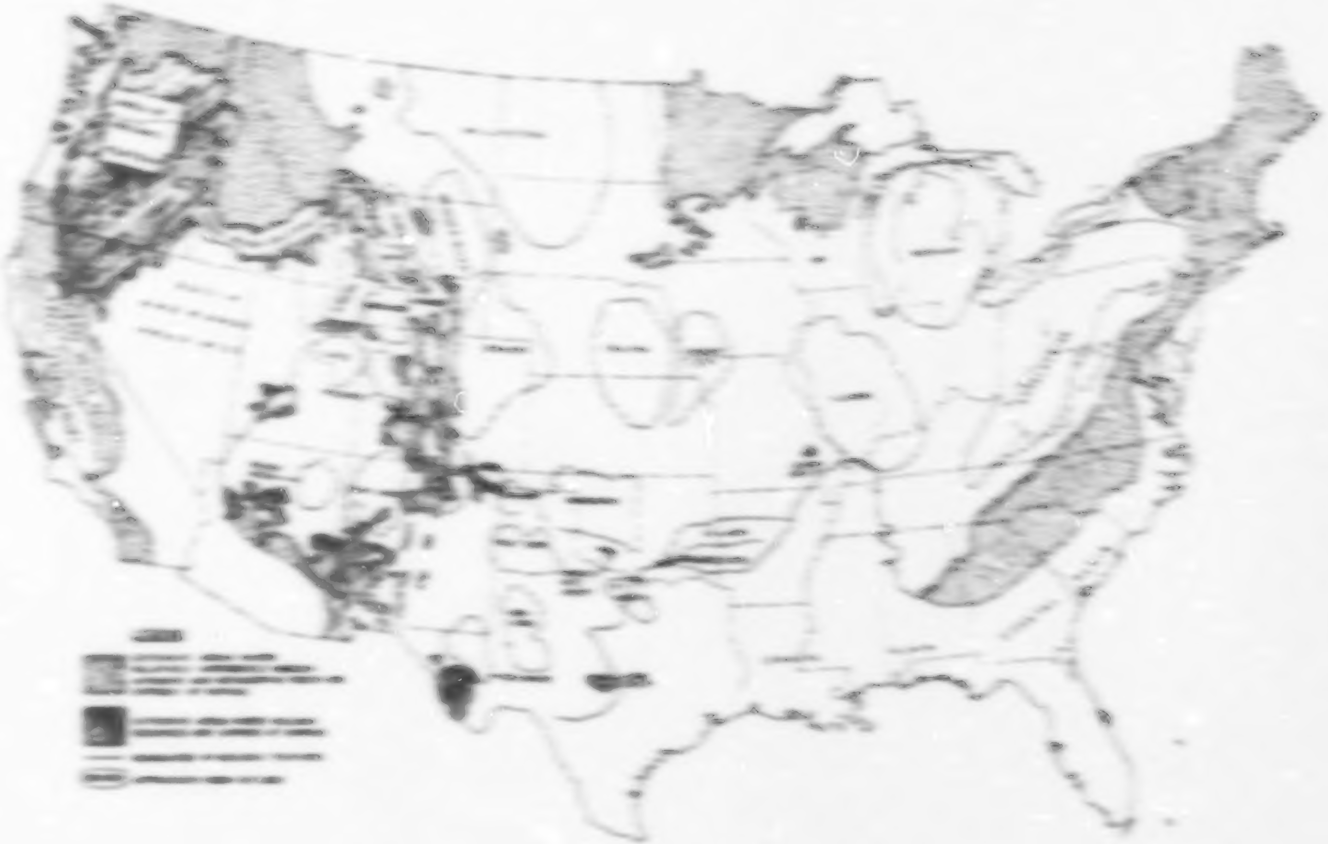

Figure 4. Geologic features significant in evaluating sites for deep-well injection

enough useful information to ensure safe construction of injection wells would be extremely great. Also, the bounding limits of many of the basins, in all probability, would define a reservoir with a capacity to receive only small volumes of injected waste.

The geology of the west coast is complex and in many areas, not too well known. In southern California, several relatively small Tertiary basins have yielded great quantities of oil and gas. Geologically, these basins probably could be considered satisfactory sites for waste injection wells. However, the speculation on many factors, such as possible contamination of future water supplies, contamination of oil and gas reservoirs, and triggering of active fault zones prevent these basins from being considered as attractive for deep-well injection of any industrial waste at this time. Eocene sands in the subsurface of the Sacramento Valley of California are being used successfully for the injection of photographic laboratory wastes, while injection problems are reported with hydrocarbon injection into Paleocene sands in Contra Costa County. Along the coast of northern California, Oregon, and Washington there are basins similar to those of southern California, but little is known about their geology.

Areas not underlain by major basins or prominent geologic features generally may be satisfactory for waste disposal if they have a sufficient thickness of sedimentary rocks that contain water, and if potential disposal zones are sealed from fresh-water aquifers by sufficient thicknesses of aquicludes or aquitards.

Seismicity

The seismic risk of various areas of the United States is outlined on Figure 5[1]. Seismic risk should be a consideration in the planning of all deep-well injection systems, and especially those handling toxic and hazardous wastes. Over all system design, including surface treatment plant, casing string design, fail safe devices, and monitoring systems should be designed and constructed corresponding to the degree of seismic risk assigned to the site area.

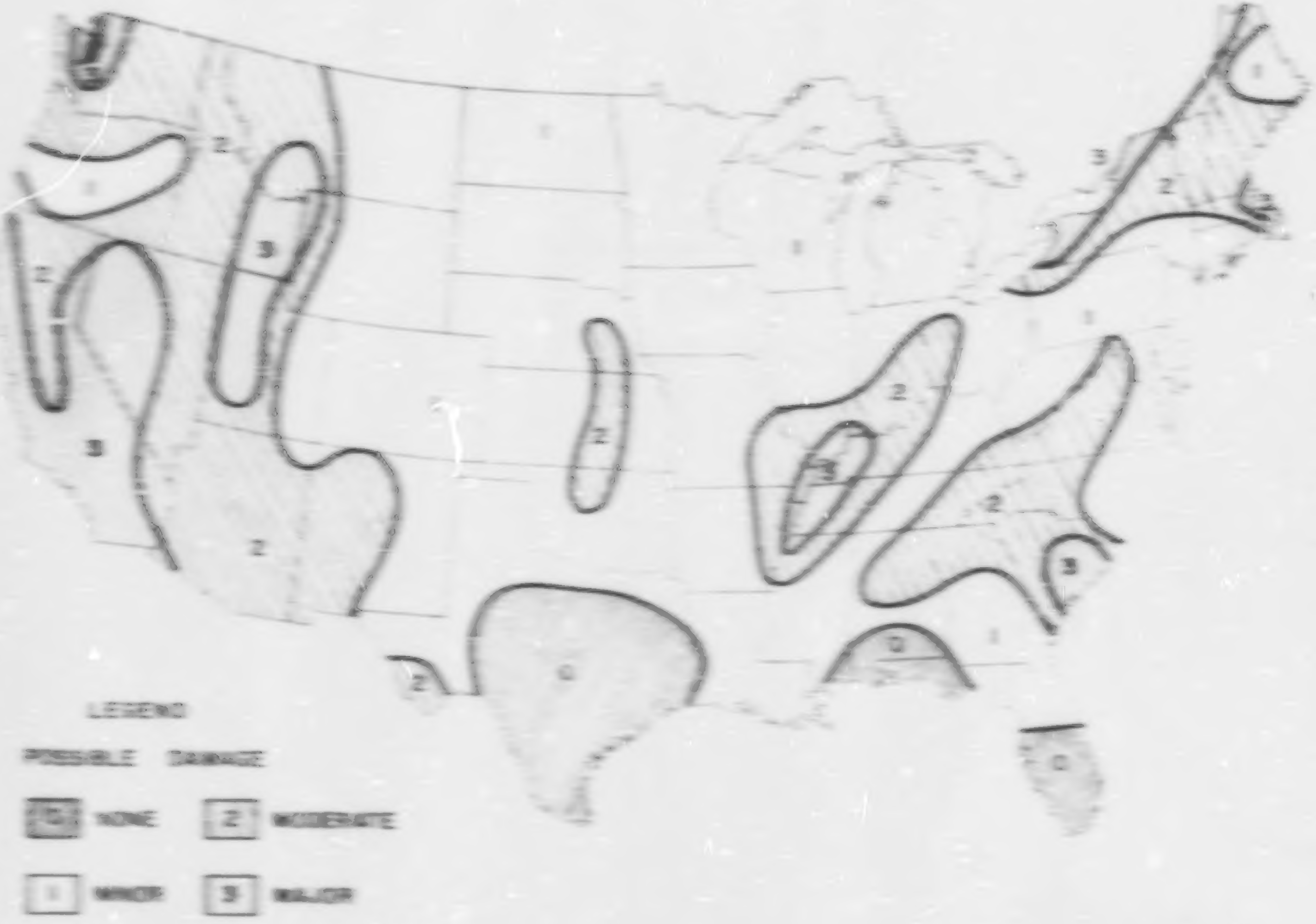
LEGEND
POSSIBLE DAMAGE
0 NONE
1 MINOR
2 MODERATE
3 MAJOR
0
1
2
3

Figure 5. Seismic risk areas of the United States (after Algermissen)

Reservoir Requirements

Suitable disposal zones are those with proper injectivity and storage capacity characteristics. There is the universal requirement that the waste be confined to the disposal formation so that commercially valuable natural resources including fresh water be protected. The ideal characteristics for an injection reservoir which follow have been expressed in one form or another by most writers on this subject. These criteria were presented originally in approximately this present form by McLean[4] and were later expanded by Reeder[5,6] to approximately the form presented in this report. The identifying terms for these criteria are, for the most part, relative and elude exact dimensions. Preciseness is difficult in defining the terms because of the large number of variables associated with any given deep-well system. However, once proposed operating conditions for a specific system have been established within a limited range, maximum or minimum mathematical limits may be assigned to the desired reservoir requirements. Ideally, to have a system that will operate safely and efficiently, the formation should possess the following characteristics:

Uniformity -

Uniformity of the reservoir rock facilitates calculations of the behavior of the injected fluid, projected volumes of fluids, injection pressures and other associated operating problems.

The necessity of reservoir uniformity is of increasing importance as the thickness of the reservoir decreases and as the volume and rate of injected fluid increase. Gradual changes over a large area or a very localized disruption in the homogeneity of a host reservoir usually do not cause great problems. However, abrupt changes in lithology, and mineralogy, leading to reduced porosity, permeability or other reservoir characteristics related to storage capacity or transmissibility can not only increase the scope and magnitude of operating problems, but can make an entire operation physically impossible.

Large Areal Extent -

A reservoir of large areal extent is necessary to take injected fluids in sufficient quantity to make a disposal project a mechanical and economic success.

The areal extent, like uniformity, is a relative parameter dependent upon many variables, and it must be determined for each well. The rate and volume of waste to be injected, the length of time during which it is injected, the total volume expected to be injected, whether the reservoir is confined or unconfined, and whether the reservoir fluid contains gas in solution are some of the factors which must be known before definite mathematical limits can be defined. A reservoir of infinite extent and of homogeneous lithology would represent an ideal situation for an injection zone. Inasmuch as this condition is nonexistent, the exact dimensions to be assigned a reservoir of "large areal extent" must be determined as the smallest available to safely satisfy the conditions needed for the injection program of the proposed injection well. However, it is advantageous to have a reservoir larger than the needed minimum to take advantage of the micro-space donations made by fluid and rock compressibility which is valuable only in the macro proportions gained in large volumes over large areas.

Substantial Thickness -

This relates directly to the volume of the reservoir available for injection. However, it is of more importance in its direct relationship to the rate at which the formation will take injected fluid. It will vary with the requirements of each individual system and changes in their requirements. The maximum available thickness in an injection zone should always be an objective in planning an injection well if it can be obtained without adversely affecting the other parameters to be considered in selecting the well site.

High Porosity and Permeability -

These factors relate directly to available volume and to the rate at which fluid can be injected at reasonable pressure.

The maximum obtainable porosity and permeability in an injection zone is an asset and usually is an aid to a trouble free and smoothly operating injection system.

Low Pressure -

This is a desirable factor in all cases inasmuch as it allows a greater working margin at which fluids can be injected into a reservoir without causing fracturing. Too high initial pressures may be a factor limiting the intake rate and operating life of the injection well, as well as greatly increasing the operating cost.

Salaquifer -

The minimum salinity of water in the host formation generally will be specified by regulatory agencies in most states, but will be at least 1000 ppm total dissolved solids except under unusual circumstances. However, because of its relative freshness, ease of treatment, use in stock watering, irrigation of certain crops and use as a protective buffer, the minimum salinity at the point of injection into the host reservoir in most cases should be 10 000 ppm. This does present problems in some regions and needs more detailed study. Salinity of formation water is discussed in detail in another section.

Separated from Fresh Water Horizons -

The minimum depth of burial for a confined reservoir can be considered to be the depth at which a salaquifer is present; it may range from a few hundred feet to several thousand feet. Injection should be vertically below the level of fresh water circulation and confined vertically by rocks that for practical purposes are impermeable to waste liquid.

In an unconfined reservoir the depth of burial can be considered to be the depth at which brine is encountered in the reservoir with the freshwater zone of the reservoir being adequately separated from the injection point by a buffer of brine, salt, and brackish water.

Adequate Overlying and Underlying Aquicludes -

Vertical confinement of injected waste is important, not only for the protection of the usable water resources, but also for the protection of developed and undeveloped deposits of hydrocarbons and other minerals. The effect of lateral movement of waste on such natural resources also must be considered. Unfractured shale, clay, slate, anhydrite, gypsum, salt, marl, bentonite and similar low permeability lithologic types are considered good seals against vertical migration of fluids. Limestone and dolomite may be satisfactory confining strata. However, those rocks often have fractures and solution channels so their adequacy must be determined in each case. Fortunately, potential host zones in many places are enclosed by hundreds and occasionally thousands of feet of impermeable strata which virtually ensures their segregation.

No Inadequately Plugged Wells Near the Injection Wells -

Unplugged or improperly plugged wells that penetrate the host zone provide a means of escape for injected waste to mineral zones, groundwater aquifers or to the surface. The contamination of any zone outside the host rock completely defeats the concept and philosophy of underground waste injection.

In established oil producing areas the consideration of unplugged or improperly plugged wells is probably the most important parameter once the presence of an adequate injection horizon has been determined. This is because a large percentage of wells when plugged have been filled only with mud, and have had no cement bridge plugs spotted at any interval within the well bore. Mud laden fluid will, in time, tend to settle out thereby reducing its effectiveness as a plugging agent. Any pressure increases because of injection in any zone exposed to this mud filled well bore will cause a fluid movement toward this area of less resistance once the pressure of the mud column is equalized. With a sufficient increase in pressure, a steady flow up the abandoned well bore will invade any horizon with a lower pressure differential. It should be noted that the formation water is quite often the escaping fluid rather than the injected waste which usually does not migrate too far from the point of injection. The earlier the date of development of a particular producing area the more critical the poorly plugged well problems become when planning a deep-well injection system in the same area.

Compatibility Between Reservoir and Injected Wastes -

The waste must be compatible with formation lithology, and to a degree with the native fluids of the formation. Although, in the latter case incompatible waste may be safely injected behind a compatible buffer fluid. In most cases, compatibility of the injected waste with the formation fluid is probably the least important of all the criteria for safe deep-well injection, as preinjection treatment can eliminate the problem in a large majority of the cases.

Incompatibility between formation and injected fluids must not, however, be ignored as early recognition and remedy of this condition can mean the success or failure of a deep-well system. Incompatibility between waste fluids and formation minerals is a much more critical condition, when encountered, and is much more difficult to combat successfully than reaction between the fluids.

Compressibility

Both the reservoir rock and the interstitial fluid are compressible to a very small degree. It is the compression factor that provides the space needed to inject extraneous fluids into an otherwise full reservoir. The waters in the salaquifer are compressed by the injected waste liquids in an ever expanding cylinder away from the well bore. Since rock and water compressibility are both of small magnitude, the salaquifer must be of large areal extent to distribute the pressure build-up. If the formation is confined by faulting, reservoir pinch-out, or permeability restriction in the region of the disposal well, a very limited area will be available to compress the formation rock and water, and pressure will build up rapidly, or injection rates decline to a point where the operation becomes impractical.

Water Compressibility -

The compressibility of pure water is known to be dependent upon the pressure, temperature, and gas in solution in the water. There is a wide range of compressibilities for water, increasing pressures having the effect of reducing the value whereas increasing temperatures have the effect of producing an increase. Expressed in cubic metres per cubic metre per degree kelvin, the compressibility of pure water at 41.4 MPa (6000 psia) and 366.5 K (200° F) is approximately 4.6 x 10^{-5} m^3/m^3/MPa (2.9 x 10^{-6} barrels/barrel/psi). Since with increasing depth higher pressures and temperatures are encountered, it is expected that compressibility will increase but that the magnitude will depend on the relative increases in pressure and temperature.

At a given pressure and temperature, the effect of gas in solution in pure water is to increase the compressibility over that of pure water at the same pressure and temperature. The effect of gas solubility from the compressibility is considerable as a reservoir water containing 3.56 m^3 of natural gas per m^3 (20 cubic feet per barrel) will have a compressibility approximately 19 percent greater than that of pure water at the same temperature and pressure.[7]

Rock Compressibility -

The porosity of sedimentary rocks has been shown by Krumbein and Sloss[8] to be a function of a degree of compaction of the rock. The compacting forces are a function of the maximum depth of burial of the rock. Sediments which have been buried deeply, even if subsequently uplifted, exhibit lower porosity values than sediments which have not been buried at a greater depth.

Apart from the compaction on grain arrangement, rocks are also compressible. Geertsma[9] states that, three kinds of compressibility must be distinguished in rock: (1) rock matrix compressibility, (2) rock bulk compressibility, and (3) pore compressibility. The compressibility of each parameter above is the fractional change in volume by that parameter with a unit change in pressure. Data reported by Fatt[10] are correlated with a so-called "net overburden pressure" defined as (P*0.85P). The factor 0.85 is introduced to take into account that the internal pressure does not wholly react against the external pressure. The factor is believed to be dependent upon the structure of the rock and range from 0.75 to 1.00 with an average of 0.85. Fatt found that the core compressibility was a function of pressure. Within the range of data considered he did not find a correlation with porosity. Pore volume compressibility of consolidated sandstones is in the order of 5×10^{-6} to 10×10^{-6} reciprocal psi.[7]

Critical Pressures of Confining Beds -

Impermeability of overlying and underlying beds is essential so that the possibility of breakthrough from pressure of injection, pressure from evolved CO_2, or thermal expansion does not take place. All operating pressures should be below the critical pressure needed to fracture the formation.

Theoretical overburden pressure of the earth is equal to 22.6 kPa/m (1.0 psi/ft.) of depth. The effective overburden pressure, that pressure required to inject fluid into a fractured well, varies from 17.0 kPa - 25.1 kPa/m (0.75 - 1.11 psi/ft.) of depth at 610m (2000'), to 12.9 kPa - 19.2 kPa/m (0.57 - 0.85 psi/ft.) at 2438m (8000').[11] Extremes may range from 9.0 kPa - 33.9 kPa/m (0.4 - 1.5 psi/ft.) of well depth.

In order to design adequate surface and pumping equipment, and to accurately evaluate the hydrologic properties of the disposal formation, injectivity tests should be made. McLean[5] suggests, if possible the tests should be made at the critical input pressure, i.e., the point at which the formation begins to fracture, and in this way determine the maximum safe injection pressure. Although, injecting at this critical pressure will determine the maximum safe injection pressure, working so close to the critical formation pressure may invite breaching the integrity of the overlying or underlying aquicludes. If the integrity of the aquicludes is breached, the governing concept and philosophy of deep-well injection and waste containment is nullified.

Natural and Artificial Escape Routes -

Faults, joints, or fractures from excessive pumping pressures, formation outcrops, and unplugged or poorly plugged wells, all represent potential escape routes for injected waste fluids. However, many operations can be conducted within the restrictions imposed by the factors above, but each factor mentioned deserves serious consideration when conducting a feasibility study for deep-well injection.

Artificial Fracturing to Increase Permeability -

Permeability may be increased by artificially fracturing the formation and propping the resulting fractures with silica-sand, glass beads, aluminum pellets, nutshells or other such agents.[11] Table 7, modified after Wright[12], shows the calculated effect of stimulation of an injection well.

Accidentally induced fractures may be produced when critical pressures are exceeded in pumping. Unless these fractures are propped, they will usually close when pressure is relieved. However, these fracture zones once established will remain zones of weakness and will probably respond to lower pressures as injection proceeds.

The natural tendency will be for a relatively high percentage of the fractures to be horizontal when they are developed at depths of less than 300m (1000'). At depths greater than 300m (1000') fractures will, in almost all cases, be vertical. McLain[11] concluded that the most probable mechanism of failure of the rock appears to be by the formation of a vertical instead of a horizontal fracture. He further states that the fracture is controlled primarily by the orientation of the principal stress field in the rock, and that each successive waste injection slightly modifies this stress field towards a condition more favorable to the formation of a vertical fracture. Sun[15] developed a mathematical model for an impervious homogeneous, isotropic medium, for calculating the amount of uplift to the ground surface, the maximum separation of the horizontally induced fracture at the injection well site at the radius of extension of the fracture. He concluded that if the bottom-hole injection pressure is greater than the overburden pressure, and the observed uplift is nearly the same as the calculated uplift, the fracture orientation is probably nearly horizontal. He cites the validity of the mathematical model being tested by uplifts from nine injections made at the Oak Ridge National Laboratory, Tennessee, from 1960 through 1965.

Table 7. CALCULATED EFFECT OF STIMULATION OF AN INJECTION WELL

Year	dam^3 (Gallons x 10^6) Per Year	Total dam^3 (Gallons x 10^6)	Pressure Increase kPa (psi) Not Treated	Pressure Increase kPa (psi) Treated	Improvement* kPa (psi)
1	138.1 (36.5)	138.1 (36.5)	938 (136)	476 (69)	462 (67)
2	138.1 (36.5)	276.3 (73.0)	965 (140)	503 (73)	462 (67)
3	276.3 (73.0)	552.6 (146.0)	1917 (278)	993 (144)	924 (134)
4	276.3 (73.0)	829.0 (219.0)	1958 (284)	1034 (150)	924 (134)
5	414.5 (109.5)	1243.5 (328.5)	2916 (423)	1531 (222)	1386 (201)
6	414.5 (109.5)	1658.0 (438.0)	2965 (430)	1579 (229)	1386 (201)

Conditions: Porosity 20%, Permeability 250 md.
Thickness 18m (60'), Viscosity 0.5 cps.

*Assuming fracture treatment increased well radius to 30.4m (100').

Hubbert[11] from field observations and laboratory experiments felt the following general conclusions to be warranted. (1) Underground stress is not generally hydrostatic but depends upon tectonic conditions. The least stress will be approximately horizontal in tectonically relaxed areas characterized by normal faulting. The least stress will be approximately vertical and provided the deformation is not too great, approximately equal to the overburden pressure in areas of tectonic compression, characterized by folding and thrust faulting. (2) Hydraulically induced fractures should be formed approximately perpendicular to the least principal stress, being vertical in tectonically relaxed areas and horizontal in tectonically compressed areas. (3) Breakdown or fracturing pressures are affected by the values of the pre-existing regional stresses, by the whole geometry including any pre-existing fissures, and by the penetrating quality of the fluid. (4) Minimum injection pressures depend solely upon the magnitude of the least principal regional stress and are not affected by hole geometry or the penetrating quality of the fluid. In tectonically relaxed areas, the fractures should be vertical and should be formed with injection pressures less than the total overburden pressure. In tectonically compressed areas, provided the deformation is not too great, the fractures should be horizontal and should require injection pressures equal to or greater than the total overburden pressure. (5) It does not appear to be mechanically possible for horizontal fractures to be produced in relatively undeformed rocks by means of total injection pressures which are less than the total pressure of the overburden. (6) In geologically simple and tectonically relaxed areas, not only should the fractures in a single field be vertical, but they should have roughly the same direction of the strike. (7) Vertical fractures intersecting horizontal permeability barriers will facilitate the vertical flow of fluids.

A question of serious concern in deep-well injection is the vertical migration of fluids. Undoubtedly vertical fractures will facilitate the vertical migration of fluids where the fractures cut underlying and/or overlying aquicludes. In breaching these barriers they may create communication between reservoirs not otherwise in communication, thus causing injected wastes to escape from the designated host reservoir into other reservoirs, possibly contaminating future reserves of mineral resources and fresh water horizons. This generates a critical situation when highly toxic or hazardous wastes are being injected, especially if they have long persistance periods or will not break down into more innocuous substances. Such waste types if they escape have the potential to be a contaminant and threat to the environment for an undetermined period of time. Hubbert[11] stresses the need for a development of down-hole instruments by means of which, not only the vertical extent, but also the azimuth of the fractures, can be determined.

Pressure Distance Time Relationship -

An important, but little understood consideration is the pressure effect, at various distances from the well bore at given times and volumes of injected fluids. Where legal situations may develop, or where disposal is conducted in the vicinity of potentially valuable mineral deposits, this factor becomes very important. This information is useful in predicting long range reservoir performance in design of injection equipment, and the effect on unplugged wells in the vicinity. The rate at which the pressure increases in a formation and the distance that this higher pressure moves radially out from the injection wells can be computed for a specific injection rate from non-equilibrium equations. If equilibrium conditions are approached, however, these equations are no longer applicable. As fluid is continuously pumped into a homogeneous uniform aquifer of infinite areal extent, the pressure radius will increase, but at a decreasing rate, due to expanding storage area available. Van Everdingen[16] and others, (Appendix A), have given the subject comprehensive treatment. Figure 6 shows pressure distribution away from the well bore of a hypothetical reservoir.[17]

Radial Fluid Travel

Radial fluid travel can be calculated initially by Equation 1 as presented by Talbot[18]. Equation 2 is the equivalent in metric (SI) terms.

These equations show single phase radial flow in a homogeneous formation. Some care should be used in applying

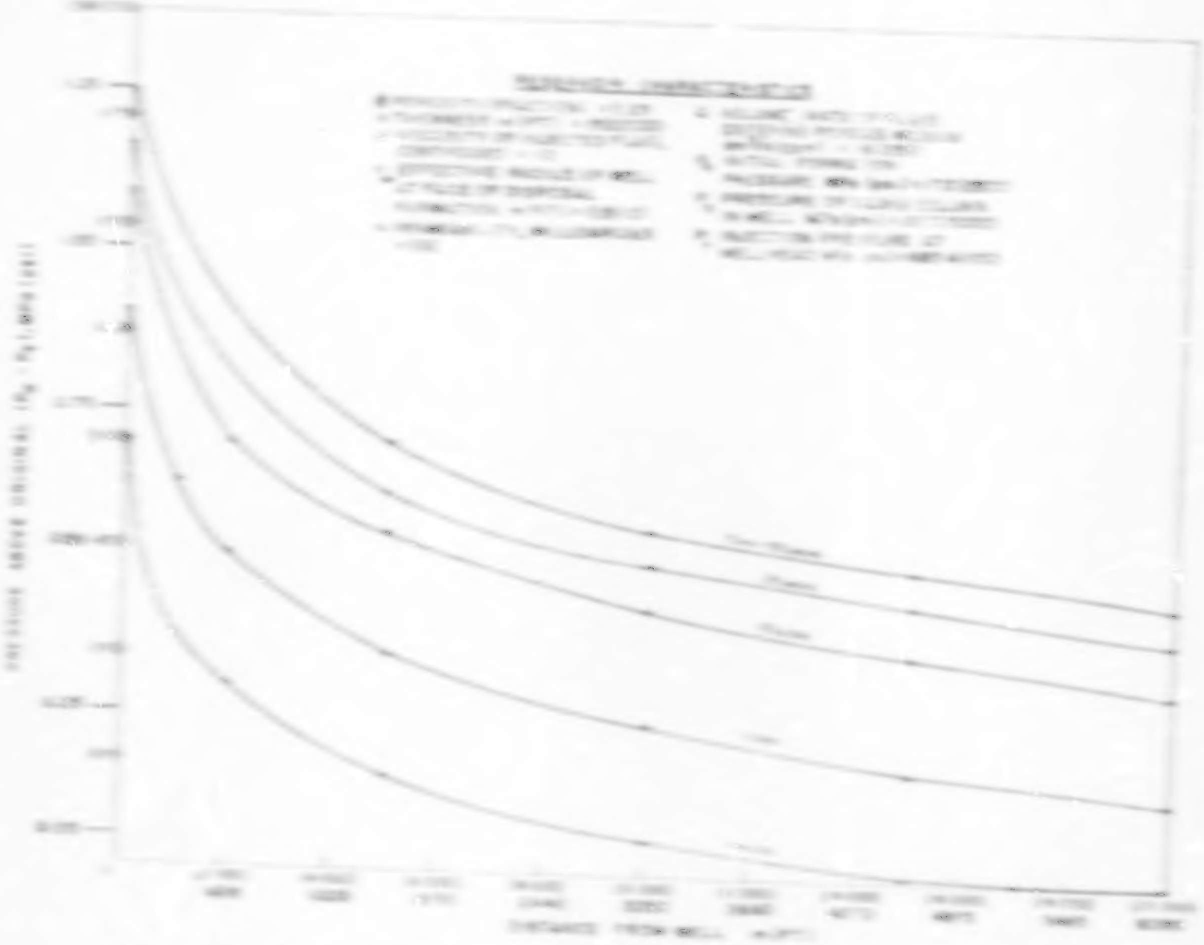

Figure 6. Pressure distribution away from the wellbore of a hypothetical reservoir

radial flow formulas to volumetric calculations, as illustrated, because most permeable formations are noted for the lack of homogeneity. However, this equation serves well in making initial estimates in radial fluid travel, and does demonstrate the very large capacity of subsurface strata.

$$R = \left(\frac{V \times \frac{1}{P} \times \frac{1}{S} \times T \times 22,300}{H} \right)^{1/2} \qquad (1)$$

Where: R = Radial distance of waste travel from well bore, ft.
V = Volume injected gpm
P = Formation porosity as a decimal fraction
S = Saturation effect as a decimal fraction*
T = Injection time, year
H = Effective formation thickness, ft.

*The term saturation effect used here by Talbot is usually termed sweep efficiency in most studies of flow through porous media, and throughout the petroleum industry.

$$R = \left(\frac{QT}{\pi \phi S H} \right)^{1/2} \qquad (2)$$

Where: R = Radial distance of waste travel from well bore, m
Q = Volume injected m^3/s
ϕ = Formation porosity as a decimal fraction
S = Sweep efficiency as a decimal fraction
T = Injection time, seconds
H = Effective formation thickness, m

Extremely detailed and comprehensive treatment of radial fluid travel has been given by Hubbert, Van Everdingen, Van Poolen, Harleman, Skibitzke, and others (Appendix A).

The subject is so involved and the many writers have treated the subject so well and in such detail that little is to be gained by attempting to summarize the work in this section. For complete coverage of the subject, it is suggested that the original papers be consulted. Figure 7, shows the effect of formation thickness on the radius of injected fluid migration.[17]

Water Salinity

The maximum salinity of water in the injection zone probably will be specified by regulatory agencies in most states[1], but will be at least 1000 mg/l total solids except in unusual circumstances. Water containing less than 500 mg/l is now considered to be acceptable as potable water used by interstate carriers,[9] although water of higher concentrations can be used for human consumption with safety. State regulations or policies establishing the minimum total dissolved solids for a reservoir receiving injected wastes vary from 1000 to 10 000 mg/l throughout the United States.

All water within the 1000 to 10 000 mg/l range of total dissolved solids, should be considered a potentially usable resource for human consumption, and is at this time in its present state usable for livestock watering and for irrigation of certain crops to a limited degree. The senior author of this report investigated studies conducted by South Dakota State University, North Dakota State University, Kansas State University, University of Texas, University of Manitoba, the Commonwealth Bureau of Animal Health of Australia, and individuals and agencies of numerous other countries outside the United States has found that the overall conclusions of these studies show that many animals can use water of relatively high salinities without adverse affects. A generalized summary of the experiments from the sources mentioned above show that the following ranges of concentrations of salts in drinking water appear to be those concentrations within which animals can function and be maintained without bodily harm.

Name	Concentrations Tolerated
Poultry	4000 - 7000 ppm
Swine	6000 - 9000 ppm

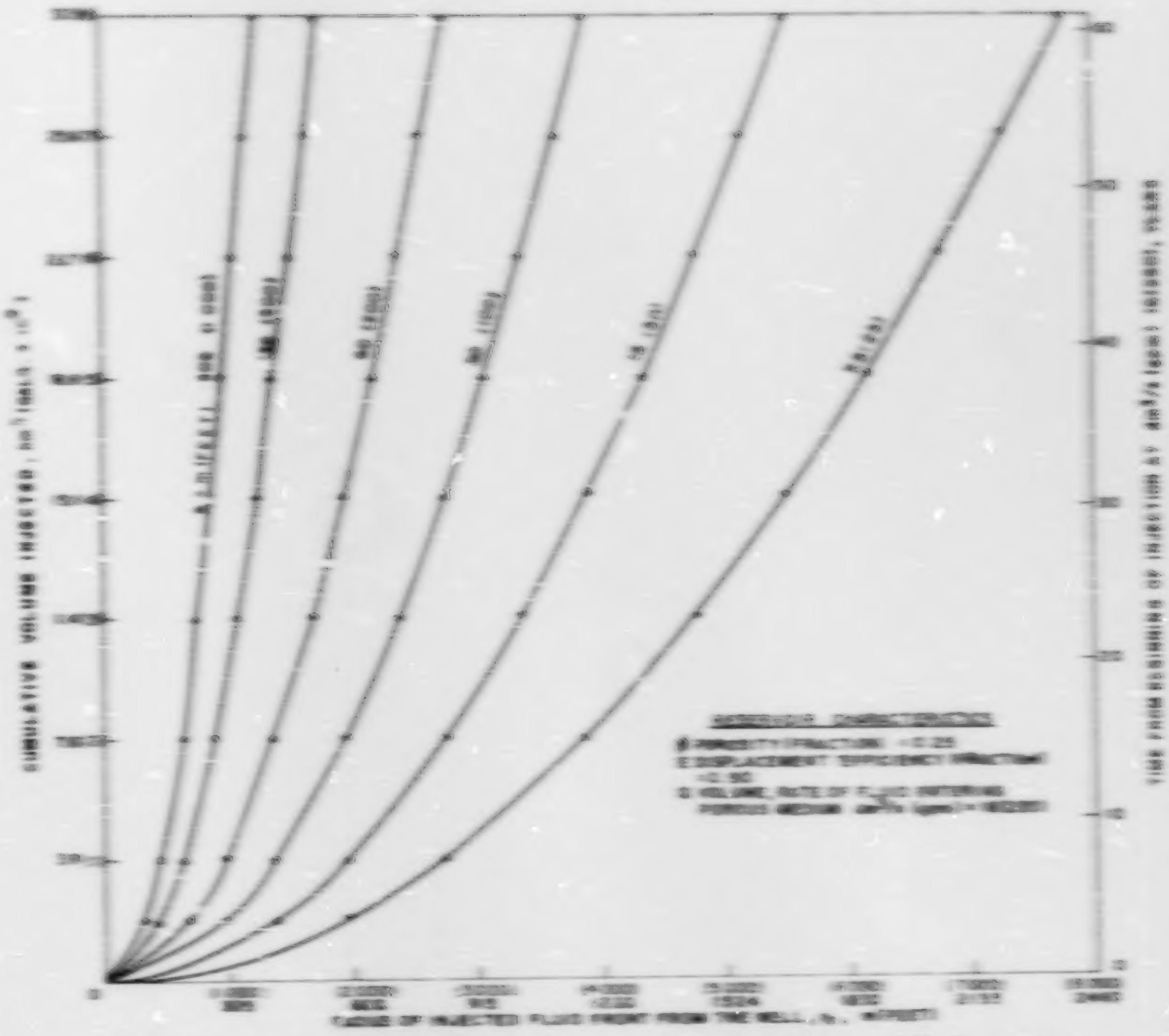

Figure 7. Effect of formation thickness on the radius of injected fluid migration

Name (contd)	Concentrations Tolerated (contd)
Horses	7000 - 10 000 ppm
Cattle	8000 - 11 000 ppm
Sheep	9000 - 12 000 ppm

ENGINEERING ASPECTS

The discussion in this section, engineering aspects of deep-well waste management, will be confined to well construction, and an idealized deep-well program with the rationale for the particular type of construction employed will be outlined. Most of the deep-well systems operating in the United States today generally have followed most of the constructional practices advocated here, but probably very few have followed all of the practices outlined.

The initial concern in the planning, construction, and operation of a deep-well management system is the protection of life and property as represented by potable waters and minerals of economic value which might be found beneath the surface of the earth.

The principal concern with the construction of a deep-well is the possibility of corrosion of the tubular goods utilized in the well and the cementing materials used to seal the casings in the ground. If a casing string or the cement sheath behind the casing string is materially damaged then an uncontrolled movement of injection fluid is not only possible, but quite probable, into zones which may very well contain minerals of value or potable water. Because of this it is recommended that all injection fluid be conducted to the injection face through a sacrificial tube, and that the casing strings be protected at all times from contact with the injected materials.

The beginning point in planning the deep-well is the tubing string which will serve to conduct the injected material to the injection face. This tubing string should be constructed of a material which has suitable mechanical properties for the depth of the well, and will have adequate flow characteristics for the length of the string and the planned rate of injection. Certain plastic or fiber reinforced plastic tubes have excellent corrosion resistance and flow characteristics; however, in most cases they are lacking in the mechanical strength which is desirable for a deep-well system. The plastic tubes also are normally limited in the pressure which they can withstand. Probably the ideal tubing would be a steel tube which has been internally coated with the plastic material of appropriate corrosion resistance for the materials to be injected. A problem which existed early in the development of plastic lined tubing was the number of holidays (a gap in the plastic coating) which would exist in the tubing string, but careful attention to the coating process and the utilization of holiday detectors has minimized this problem.

With the establishment of the optimum tubing size, the casing sizes required for the construction of the well are determined. The number of casing strings which will be utilized is determined by the conditions prevalent in the area. There also should be a minimum of two casing strings in the deep-well system and for very deep wells or unusual drilling conditions, additional casing strings should be run.

Casing lines in deep-well systems should be discouraged because of the numerous problems arising from their use. A good seal at the liner hanger is difficult, cementing a liner often does not result in a good cement sheath around the pipe, and the size reduction often causes problems when running tools and equipment down hole for workovers or cleanouts. However, the recommendation against the use of casing liners is not directed against the use of gravel packed screen liners through unconsolidated sand sections or similar uses.

The first casing string should be set at a depth sufficient to be a minimum of 15 m (50') below the lowest fresh water zone in the area and this casing string should be cemented by the pump and plug method from the bottom of the casing to the surface. Subsequent casing strings should be cemented until the cement and the annulus is at least 15 m (50') inside the next largest casing string. All casing strings should be mechanically centralized in the drilled hole to ensure a consistent thickness of the cement sheath and the highest possible quality in the cementing operation.

With the final casing string, whether it is set on top of the host zone or set through the host zone to be perforated, the cement system should be planned to be compatible with the injected fluid. An example of incompatible cementing systems and injected fluids are normal Portland cement and sulfate rich injected materials. Normal Portland cement is subject to attack by the sulfate ion with subsequent deterioration and potentially complete failure of the cement system. There are modifications possible in the cement system which will remove the threat of sulfate attack. The most common modification and most nearly ideal in most instances, is the utilization of pozzolan in the cement system. Cement systems should be designed and tested for compatibility with the injected material prior to construction of the deep-well. In the case where extensive modification of the cement system is required, the entire system need not be modified, but perhaps the last one hundred feet of cement sheath above the injection zone be of the modified composition.

Probably the most important protective measure which can be taken in the construction of a deep-well is the cementing of the casing from the bottom of the casing string well into the next casing string. This procedure will protect the casing from external corrosion by virtue of the cement sheath around it, and the maintenance of a sealed annulus between the injection tubing and the casing with a non-corrosive fluid filling the annulus. Figure 8 is a schematic diagram of a completion and cementing program designed for maximum protection of hardware and zones outside the host reservoir for all waste types now being injected.

Another safety feature which is possible is the utilization of an extra casing packer which is set after placement of the cement to form an additional seal between the casing and the annulus. At least three manufacturers produce these packers which when set after the cementing operation become an integral part of the cement system. These packers provide an elastometric seal between the casing and the borehole so the elastometer selected for these packers should be one that is not subject to attack by the injected materials.

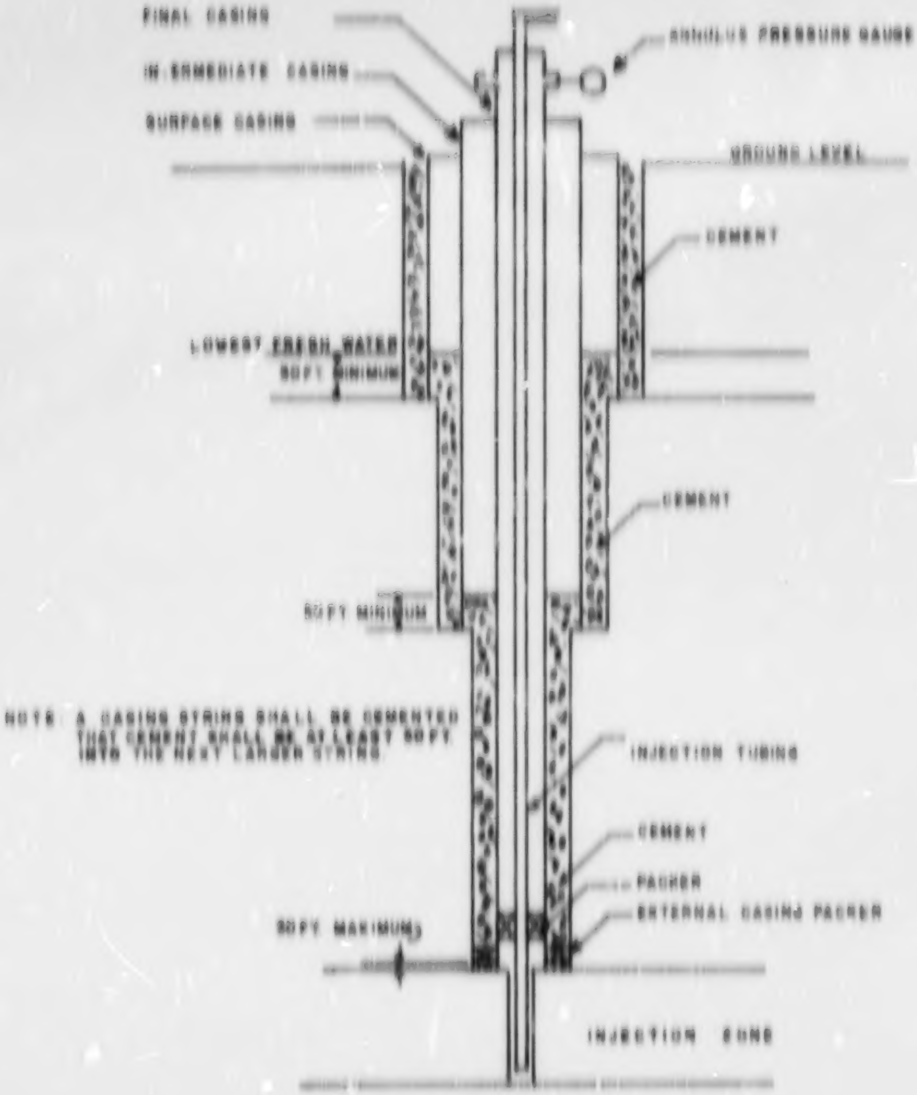
FINAL CASING
INTERMEDIATE CASING
SURFACE CASING
ANNULUS PRESSURE GAUGE
GROUND LEVEL
CEMENT
LOWEST FRESH WATER
50FT MINIMUM
CEMENT
50FT MINIMUM
NOTE: A CASING STRING SHALL BE CEMENTED THAT CEMENT SHALL BE AT LEAST 50FT INTO THE NEXT LARGER STRING
INJECTION TUBING
CEMENT
PACKER
EXTERNAL CASING PACKER
50FT MAXIMUM
INJECTION ZONE

Figure 8. Completion recommended for maximum protection during waste injection

Completion Types Illustrated

Two types of typical well casing programs used in waste disposal wells are shown in Figure 9. The left diagram shows an open hole completion in which the long string of casing is set at the top of the injection zone and cemented to the surface. The injection zone is uncased if it is in a competent formation. A perforated liner may be installed in the open hole section to prevent cave-ins from closing off a part of the injection zone. The right hand diagram shows a cased hole completion in which the long casing string is set through the injection zone and cemented. The casing is then perforated opposite the injection zone to open the wellbore to the formation. Note that both wells have an outer, or surface, casing which is set at a depth below the deepest "usable" water zone and then cemented to the surface. These diagrams show waste being injected through the long string. This is not recommended for several reasons:[11]

a) The waste fluid is in contact with the protective casing string. Corrosion of this casing may terminate the useability of the well or cause an expensive repair requiring a new and smaller string of casing.

b) Corrosion products may plug or severely reduce the capacity of the injection zone.

c) A casing leak could occur and not be detected for a considerable period of time. This would permit the escape of the wastes to a formation other than the injection zone.

Figure 10 shows three well diagrams. The left diagram is of a well in which the tubing is allowed to hang free. In this type of completion, the annular space is filled with a fluid such as fresh water or fuel oil and then shut in at the surface. This completion has the same disadvantage as a well without tubing insofar as detecting leaks in the casing. The middle well illustrates a type of tubing completion used in some waste disposal wells. The tubing is set in a packer located down in the injection zone below the top. Water is injected through the annulus into the top of the injection

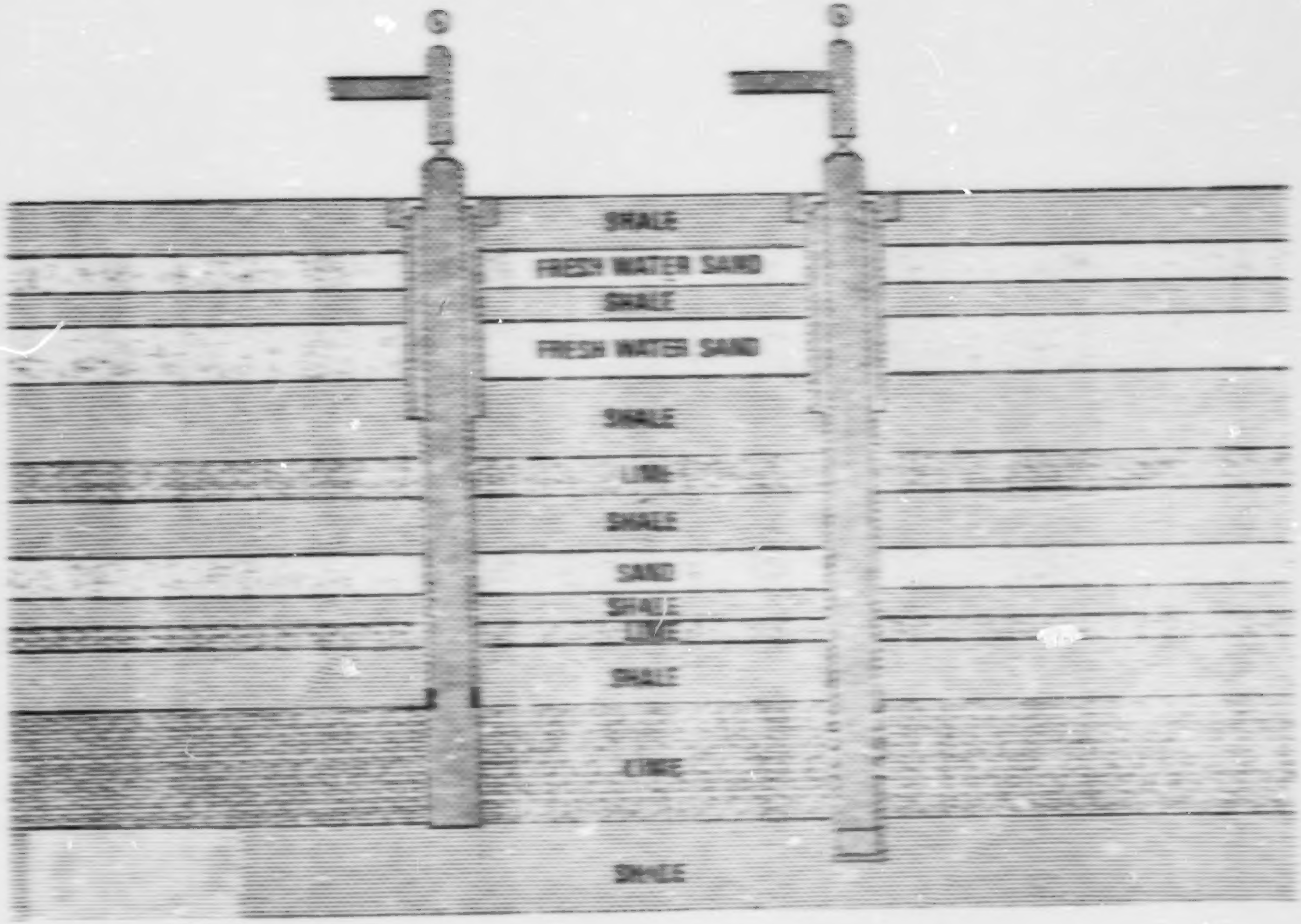
SHALE
FRESH WATER SAND
SHALE
FRESH WATER SAND
SHALE
LIME
SHALE
SAND
SHALE
LIME
SHALE
LIME
SHALE

Figure 9. Basic well casing programs used in waste-injection well completions

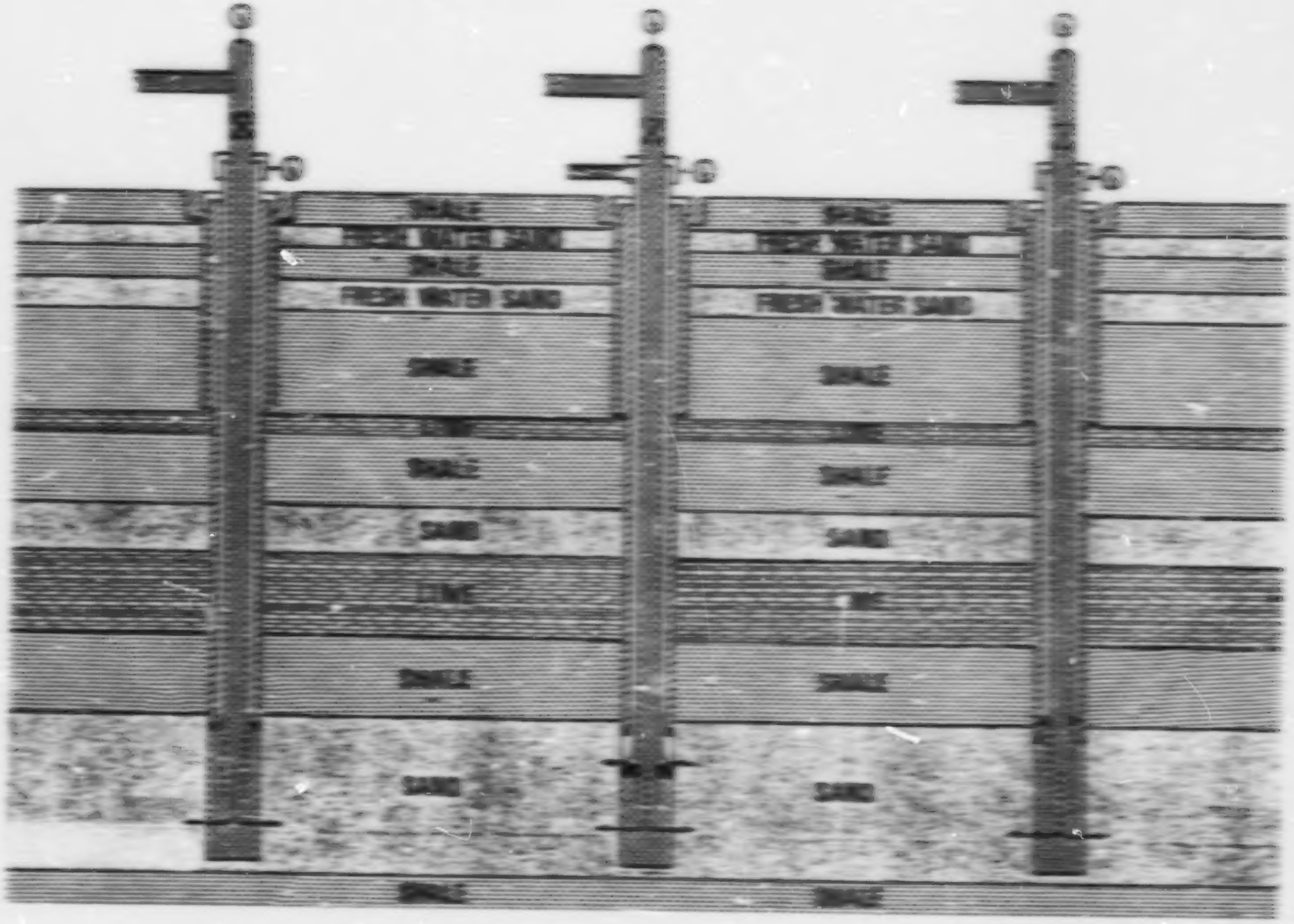
SHALE
FRESH WATER SAND
SHALE
FRESH WATER SAND
SHALE
LIME
SHALE
SAND
LIME
SHALE
SAND
SHALE

Figure 10. Three types of completions used in waste-injection wells

zone above the packer while the waste fluid is injected through the tubing into the lower portion of the injection zone. This design has the same disadvantage discussed for the previous completion method in that the casing is subject to the injection pressure, the detecting of any casing leaks is not positive, and corrosion of the casing and tubing will undoubtedly be experienced. In addition to the substantial expense necessary for the injection of the water into the annulus, this reduces the capacity of the well for waste disposal. The right hand diagram shows the type of completion generally favored for injection wells. The tubing is equipped with a packer, of suitable construction to resist deterioration by the waste material, which is set in the casing above the disposal zone. The packer provides a seal to isolate the annulus space above the packer from the waste fluids, and may need to have the bottom portion made of a special alloy such as stainless steel or a plastic-coating may suffice depending on the nature of the injected material. The annulus space is filled with an inert liquid such as oil with a corrosion inhibitor in it and placed under pressure. Should there be a failure of the tubing or packer or casing then the annulus pressure will change which will serve as an alarm indicating leakage. Injection can then be stopped until repairs are made. With the fluid filled pressurized annulus, a packer or tubing leak will be detected at the surface as decreasing pressure if injection pressure is lower than the annulus pressure and as increasing pressure if the injection pressure is greater than the annulus pressure. Should a casing leak develop, this will manifest itself as falling pressure at the surface as the annulus fluid is lost through the casing leak. A tail pipe of noncorrosible material may be extended below the packer as illustrated in the diagram. A light noncorrosive fluid or inert gas may be placed in the space around the tail pipe below the packer, thus providing protection for the packer and casing at this point. The type completion just described offers the greatest protection of the casing, thereby affording the best protection for zones other than the injection formation.

If the practices of the recommended completion procedure are followed, the integrity of the casing string is virtually assured for beyond the useful life of the deep-well. Even when severe corrosion attacks on the injection tubing have caused its deterioration to a degree where it can no longer be used for injection, it can be replaced without violating the integrity of the casing string. Also, if desired as a policy of preventive maintenance, the injecting tubing may be replaced at regular intervals before failure of the string occurs.

CHEMICAL ASPECTS

In determining whether or not a waste is suitable for injection into deep-wells, the chemical properties of the waste, the formation minerals and the interstitial fluids are very important. Precautions must be taken so that the waste itself will not harm the environment, and that there will be no reactions; or, if any reactions do take place, they will not be harmful.

Most streams which are disposed of by injection into deep-wells do not consist of only one chemical, but are usually several chemicals mixed. In some mixed streams, some or all of the characteristics of the individual constituents may exist. In others, reactions may occur which will produce entirely different characteristics[20]. The reactions which would take place upon mixing may not be known and thus make results unpredictable. These reactions which take place may produce materials which are more hazardous than any of the materials prior to mixing or they may cancel any hazardous effects which existed in the individual components. There is still much to be learned about the toxicology of materials, expecially the effects of exposure to them in low level concentrations over a long period of time. This lack of knowledge is further complicated by mixing different wastes into one waste stream. Care should be exercised by those handling waste to prevent coming in contact with it and to prevent the escape of any of the material outside of the area where it is confined awaiting disposal.

Chemical Effects on the Environment

It is important to know as much as possible about the waste and the environment into which it is injected before injection is started, because once the waste is put underground there is practically no control over it.[21] There will be some changes in the reservoir regardless of the compatibility of the waste and host. The ground water system is changed and fluids containing diffeyent chemicals from those of the native fluids will enter the receiving aquifer. In some cases, the quality of ground water is lowered, the natural resources existing in the subsurface are contaminated and there can be reactions between the waste water and natural water, or reactions between the waste water and the rock in the interval where the injection is made.

The impact on the environment of most concern to the public and regulating agencies, is that of contamination of potable ground water. Contamination can occur by escape of waste water from the underground storage area where it is injected, into a fresh water aquifer. Escape can be caused by corrosion of the casing by unneutralised acid being pumped into the well. The acids could cause corrosion of equipment both above and below the surface. Once the waste has reached the injection zone, it is possible for the waste to escape vertically into fresh water aquifers through confining beds.[77] Channels can be cut or dissolved through these confining beds by the waste if there are minerals in the beds which are soluble or reactive with the chemicals in the waste water. Other means by which the waste can escape from the injection zone include nearby improperly plugged or cemented wells or those which have corroded or insufficient casing. The warte could also escape laterally by travelling into fresh water zones in the same aquifer[77] or by entering a circulating stream which could transport them into other areas.

Near Belle Glade, Florida, lateral movement of waste being injected into a disposal well at rates ranging from 0.025 - 0.050 m^3/s (400 - 800 gpm) and operating fall, winter and spring, had reached a deep monitor well 300 m (1000') away in 1967, injection having been started in late 1966. In 1969, 27 months after injection began, upward leakage of the waste, either around the casing or through the confining beds, was indicated by geochemical changes detected in a shallow monitor well 23 m (75') away and 427 m (1400') deep. The well was deepened in 1971, and injection was resumed in January 1972. Ten months later it appeared that 4.5 m (15') of a 7 m (23') length of mild steel casing had been removed by corrosion. The waste was hot, acidic, highly organic and contained high concentrations of nitrogen and phosphorus. The temperature range was from about 344 K - 376 K (71°C - 103°C) and the pH ranged from 3.6 to 4.5.

The geochemical effects of the upward leakage of the waste included changes in both the native fluids and the aquifer. The concentrations of calcium, magnesium, organic carbon, COD, and alkalinity in the native water were increased. The pH and sulfate concentrations were reduced and there was generation of considerable hydrogen sulfide. There was dissolution of the carbonate rocks, sulfate reduction, and anaerobic decomposition of the organics. Methane, nitrogen, and carbon dioxide were produced by organic decomposition. In this case the confining beds were unable to resist the attack of the hot acidic waste.[21]

In a well at Mulberry, Florida, which was completed at 1519 m (4984') into which industrial acidic waste was injected, injection tests indicated the dissolution of carbonate rock in the injection zone with a change in the permeability and porosity of the zone. It was also indicated that there was leakage through the confining beds. Chemical reactions could take place between the waste and the confining beds which could reduce their ability to confine the waste.[24]

An industrial organic waste was injected into a disposal well near Wilmington, North Carolina, to study the interactions resulting from injecting a waste containing organic compounds into the subsurface. Solids larger than 20 µm were removed and CaO was added to adjust the pH to 4. The aquifer used for the injection zone consisted of sandstone, gravel and limestone. It was found that first the organic acids are neutralized by the carbonates in the aquifer. Dissolution of the aluminosilicate clay minerals by the organic acids contained in the waste are also indicated. As the waste is neutralized and diluted, indications are that the organic waste is degraded microbiologically. There appeared to be plugging, due in part to methane and carbon dioxide gases produced in the reaction. Leakage was detected at the injection and observation wells. The leakage could be caused by the dissolution of aquifer solids by the organic acids. The grout sealing the wells to the confining beds may also have been dissolved by the organic acids, allowing the waste to move upward into shallower aquifers.[26]

In some cases where the confining beds above and below the injection zone are not capable of resisting acid attack, such as in the peninsula of Florida, it is questionable whether an acidic waste can be confined to the injection zone.[21] In questionable areas such as this, acids should not be injected into disposal wells, because of the great risk of contamination of fresh water and mineral resources. The plugging of the pores of an aquifer will cause a decrease in the permeability and porosity of the injection zone. This, in turn, results in either an increase in the injection pressure or a decrease in the injection rate. Plugging can be caused by solids or entrained gases in the stream or by reaction of the waste with the aquifer or interstitial fluids. Auto-reactivity of the waste constituents may also take place, after injection, at the temperature and pressure of the aquifer. Soft mushy solids and gelatinous precipitates are plugging agents as well as the hard rigid ones. Soft mushy solids, such as hydrometal oxides and sulfides would tend to adhere to the surface of the porous medium to greater extent than rigid solids.[26] Acid and aluminum nitrate waste with calcium carbonate results in a gelatinous precipitate which can cause plugging.[1] Clay minerals can also cause plugging or a decrease in the permeability of a sandstone containing them when the pH of a water is increased, the salinity is decreased, or the valence of cations in solution is decreased.

Preinjection Treatment

Usually solids in a waste stream are filtered out prior to injection to prevent plugging and in some cases, constituents which are known to react with chemicals in the aquifer to produce plugging are removed by treatment on the surface. Some of the chemical treatments employed to remove chemicals which could react in the formation to cause plugging will produce large volumes of sludge or precipitates which then present another problem, that of solid waste disposal.[27] Another method used to prevent precipitates from forming when they are expected to form from reactions between the waste and formation fluids, is to inject a fluid which is not reactive with either of them ahead of the waste to form a buffer between them.[28] There is one problem which can arise in this procedure, that is the possibility of the fluids bypassing each other in the formation.[21] Uniform distribution of the buffer is prevented by the hetergeneous nature of porosity and peramability of the rock. However, it can be expected that the waste will follow the buffer, since liquids will follow the path of least resistance.[1] Waste can also be treated to reduce the toxicity of some of the chemicals contained in it and in this way some of the streams not suitable for injection because of their toxicity may be made suitable.

Reactions

There are a number of reactions which can take place once a waste has entered the aquifer. Some of the reactions may be anticipated from a knowledge of the chemistry of the waste, the aquifer minerals and the interstitial fluids. Laboratory tests can be used to determine reactions between the three components involved.[1] Samples of the aquifer fluid and minerals are not usually available until the well is drilled, which means that tests could not be run until drilling is completed. Even using the aquifer fluids and minerals, all reactions which might take place within the formation may not be predicted in the laboratory, since the temperature and pressure of the injection zone could influence the reactions. The well should be allowed to flow until a true sample of the reservoir fluid can be obtained since the samples taken immediately after drilling will be contaminated with drilling fluids. Cores should be taken to determine the mineral character of the proposed injection and confining zones.

The reactions between injected and interstitial fluids which can cause the formation of plugging precipitates were listed by Selm and Hulse. These are:

(1) precipitation of alkaline earth metals (calcium, barium, strontium and magnesium) as relatively insoluble carbonates, sulfates, orthophosphates, fluorides and hydroxides;

(2) precipitation of metals such as iron, cadmium, zinc and chromium as insoluble carbonates, hydroxides, orthophosphates and sulfides; and

(3) precipitation of oxidation-reduction reaction products.

In Kansas, a waste consisting of cooling-tower blowdown and zeolite water-softener backwash was injected into a limestone formation. The well plugged within a year and was deepened into the Arbuckle Formation, which was more permeable. The injection capacity began decreasing as it had in the other zone. It was found that precipitates formed when chromates and phosphates used as corrosion inhibitors came into contact with barium sulfite, hydrogen sulfide and soluble iron in the Arbuckle water.[23]

Reactions can also take place which would cause the toxicity to increase when injected into subsurface environments. The anaerobic conversion of mercury and inorganic mercury to methyl mercury and the anaerobic conversion of nitrilotriacetate to nitrosamines are examples. Methyl mercury, among others, can be concentrated through food chains leading eventually to humans.[11] Examples of mercury being concentrated in food chains are: In 1960, 111 persons were reported to have died or suffered serious neurological damage near Minamata, Japan, as a result of eating fish and shellfish which had been contaminated by methyl mercury and mercuric chloride discharged into Minamata Bay by a plastics manufacturing plant. In the spring of 1970, the fish in Lake St. Clair, on the border between Canada and the United States were discovered to contain high levels of mercury.[10] The toxicity of the waste and the reactions which might take place yielding even more toxic materials should be of importance when deciding whether or not a waste should be injected into a disposal well. There is always the possibility of accidental escape of these hazardous chemicals into the groundwater system from where they may be able to migrate to potable water aquifers or to the surface.

The chemical characteristics of a waste and those of the environment into which it will be injected are extremely important in determining the suitability of the waste for deep-well disposal. Since there is almost no control over a waste once it has been injected and there is no tested method of reversing the migration or recovering the injected material, it is very important to know as much as possible about the interactions which will take place between the waste and the minerals in the aquifer, and the waste and native fluids.

Profile reports for the chemicals being injected into disposal wells are found in Appendix C. These profiles cover the chemical and physical properties, toxicity, hazards, and recommendations for handling, storage and transportation of the chemicals as well as recommendations for disposal of waste containing them. Some chemicals are treated in less detail than others because of the great variation of available information.

MICROBIOLOGICAL ASPECTS

A variety of algae, fungi, bacteria, and protozoa can live in most parts of a waste injection system (collection, storage, treatment, connecting lines, injection wells, and the receiving formation). The action of the organisms on the waste may be a beneficial biochemical degradation such as is practiced in biological waste-treatment processes before surface discharge. Or the effects may be detrimental, causing erosion of equipment; plugging of filters, screens, and injection formations; and producing toxic compounds as a result of waste degradation.

Algae are precluded by the absence of light in the injection zone, however, they may proliferate in any part of the injection system exposed to light. Protozoa and fungi are precluded by the anaerobic conditions usually present in injection zones, however, like the algae, they may proliferate in any part of the system where conditions may be favorable for their growth. Yeasts are capable of anaerobic metabolism, but their occurrence in salaquifers is not documented. Bacteria occur under the conditions of waste injection in the injection zone, and some recent studies show them to be the important organisms concerned.

Recent research (some in progress or in review) substantiates the importance of bacterial growth in the receiving formation in various dilutions of waste and salaquifer water and lead to recommendations that the role of bacteria be carefully investigated before the injection of wastes. The premise that deep-well waste injection can be used for temporary storage of wastes must be revised to the extent that many of the injected wastes will most probably be greatly modified during their storage by bacterial degradation.

The hydrogeological conditions and the chemical nature of the various toxic wastes are so variable that each injection system should be thoroughly investigated with a feasibility study before injection begins. This study should consider the biogeochemical aspects of the waste-aquifer interaction zones as well as the more traditional physical parameters.

Thorough testing of the biogeochemical inturactions of the injection zone aquifer with the waste should be done in a manner similar to the following:

a. the bacterial growth potential of the undiluted waste solution and mixtures of waste and native formation water should be determined;

b. material from the formation, preferably from well cores, should be included in the tests;

c. oxidation-reduction potentials of the test solutions should be adjusted to values which are typical of the formation. Oxygen should be excluded from the solutions if appropriate to the injection conditions;

d. the test should be conducted at temperatures and pressures that approximate the operating conditions expected during waste injection;

e. adequate data must be collected on waste chemical reactions with injection zone water, injection zone minerals, and microbial degradation under the above conditions;

f. during the testing if there is any indication of probable plugging effects, studies of the best method of microbial growth control should be determined before the problem arises;

g. any indications of erosion of the injection system hardware should be utilized in the engineering design.

Recent microbiological research related to deep-well injection and applicable to all types of waste is presented in Appendix F.

GROUND WATER USE

Usable ground water, whether potable or otherwise, is something that must be given maximum protection during all phases of deep-well injection of all types of waste. Consideration of where ground water may be encountered and how it must be protected is necessary from the moment of the deep-well site selection, during the operating life of the well, and through the plug setting upon abandonment of the well.

Table 8 shows the percentage of ground water use related to total water use by states.[11] There is no direct correlation throughout most of the United States between ground water used and injection wells drilled. However, the largest number of deep-wells in the United States are concentrated along the Gulf Coast of Louisiana and Texas which is indicative of good available host reservoirs, from most of which ground water is also drawn for domestic and industrial use.

Figure 11[11] shows the shallowest depth of water containing more than 1000 ppm dissolved solids in the conterminous United States. This concentration of solids, although technically below drinking water standards[11] and classified as brackish[11] can be misleading in planning for deep-well injection. The potential use for water with concentrations between 1000 and 10 000 ppm is great. Many cities and towns throughout the country have water supplies with concentrations of dissolved solids above 1000 ppm and water with concentrations up to 10 000 ppm may be used for stock watering.

Aquifers vary from unconsolidated to well consolidated sandstones, limestones, and volcanic rocks. Unconsolidated to semi-consolidated aquifers are found mainly along the Atlantic and Gulf Coastal Plains; in the High Plains of West Texas, Oklahoma, Kansas and Nebraska; in parts of Florida; parts of Michigan, Wisconsin, and Minnesota; the Great Valley of California, and other parts of the Sierra Cascade and Pacific Mountain Ranges; as well as portions of the Basin and Range and Colorado Plateau provinces. Consolidated aquifers are present throughout most of the rest of the country and vary greatly in their storage capacity and transmissibility. Several areas such as the Florida peninsula and the region surrounding the Great Lakes, as well as smaller areas in the Rocky Mountain, Colorado Plateau and Columbia Intermontane provinces have major prominent consolidated aquifers in addition to prominent unconsolidated ones.

Table 8. GROUNDWATER USE IN THE CONTIGUOUS

UNITED STATES FOR 1970*

EPA Region and State	Percentage of Total Use	EPA Region and State	Percentage of Total Use
Region I		Region V (contd)	
Connecticut	4	Ohio	5
Maine	5	Wisconsin	8
Massachusetts	8		
New Hampshire	8	Region VI	
Rhode Island	8	Arkansas	50
Vermont	38	Louisiana	17
		Oklahoma	59
Region II		New Mexico	50
New Jersey	16	Texas	34
New York	5		
		Region VII	
Region III		Iowa	24
Delaware	6	Kansas	63
Maryland	3	Missouri	12
Pennsylvania	4	Nebraska	55
Virginia	5		
West Virginia	1	Region VIII	
		Colorado	16
Region IV		Montana	2
Alabama	4	North Dakota	14
Georgia	12	South Dakota	58
Florida	20	Utah	16
Kentucky	4	Wyoming	4
Mississippi	37		
North Carolina	7	Region IX	
South Carolina	5	Arizona	62
Tennessee	5	California	38
		Nevada	16
Region V			
Illinois	7	Region X	
Indiana	5	Idaho	16
Michigan	7	Oregon	16
Minnesota	22	Washington	12

*Water power use excluded

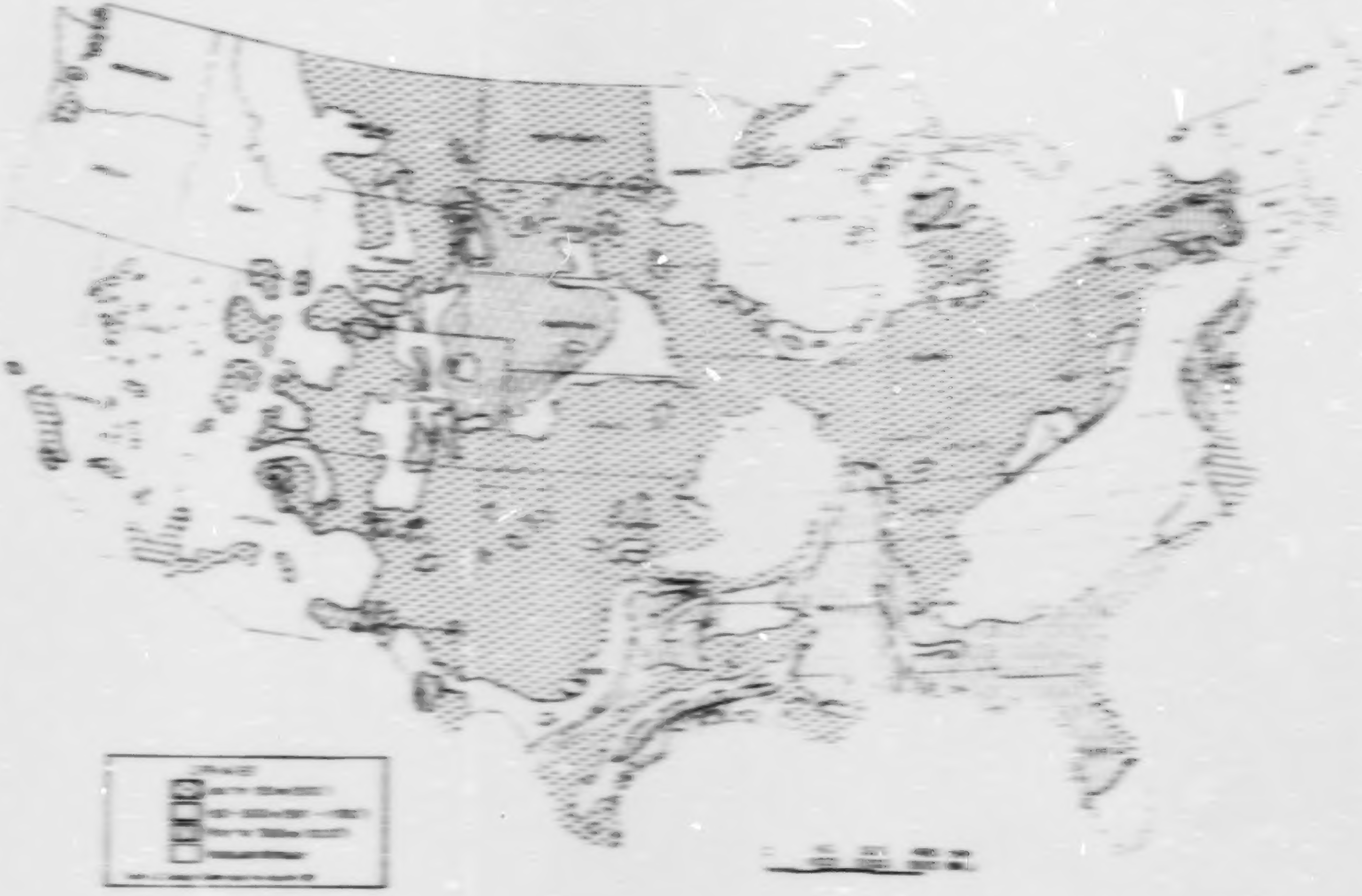

Figure 11. Depth to saline ground water in the contiguous United States

MONITORING

Monitoring of the operation of a deep-well injection and waste management system can logically be divided into four distinct functions, which are:

1. the operation of surface equipment
2. the operation of well equipment
3. the injection face operation
4. the behavior of the injected fluid in the reservoir or host rock

Pressure and injection rate are the two primary phenomenon on which most lend themselves to measurement for monitoring purposes.

Surface Equipment

The monitoring of the performance of surface equipment is accomplished by the physical inspection of the facility and the observance of pressure or rate abnormalities as signals of a malfunction in the equipment.

Operation of Well Equipment

The monitoring of well equipment is to assure the operator of the integrity of the well, and that no leaks have occured in the well tubular goods. This can be readily accomplished in a well system as outlined in the well construction section where the annulus between the casing and injection tubing is sealed by a suitable packer and the annulus loaded with a noncorrosive packer fluid under pressure. A change in the pressure recorded on the annulus is then indicative of a leak in the casing or tubing string which calls for immediate remedial action. This is perhaps the simplest of all monitoring operations, and the most vital to the protection of life and property in a deep-well system. Electrical circuits may, of course, be integrated into these monitoring schemes, thus providing automatic shutdown when a predetermined condition established by the operator is reached.

Injection Face Operation

Monitoring of the performance of the well at the injection face can be accomplished only by inference with the measurement of injection rate and pressure. The most common form of failure which might occur at the face would be reservoir plugging with precipitated material either carried to the face in the injection fluid or as a result of a reaction between the injected fluid, the host rock, and/or the fluid indigenous to the host rock. A thorough analysis of the waste to be processed, the reservoir rock, and the reservoir fluid will predict the probability of face plugging and this then can be confirmed by observing an increase in pressure and/or decrease in injection rate with increased cumulative injection.

When the injection rate falls to an intolerable level or the injection pressure rises to a level approaching that of formation fracturing or the economic maximum injection pressure, then remedial action to cleanse the face must be considered.

Reservoir Fluid Behavior

A hazard which exists in any injection program is that the fracturing pressure of the host rock will be exceeded which can lead to a breakdown of the host rock followed by an uncontrolled injection which could under certain circumstances result in the migration of injected material outside the planned host reservoir. Thus it is imperative that the fracture pressure of the host rock not be exceeded by the injection of waste material. There are no rigid rules by which fracture pressures can be predicted, and the pressure gradients vary from a low of 9.0 to > 45.2 kPa/m (0.4 to > 2 psi/ft.) of depth. Possibly the most advantageous consideration of fracture pressure and avoiding it with the injection of waste would be to determine the fracture initiation pressure upon initial conclusion of the waste well. This can be accomplished by injection at a rate sufficiently high to achieve a steadily increasing pressure, which upon reaching the fracture pressure will immediately fall off to a much lower pressure with constant injection rate. If there is no propping material in the injection fluid with cessation of pumping the fracture initiated will close and the formation will not again fracture until that pressure is reached a second time. This technique is utilized in oil and gas production to develop a base line for fracture pressures and to establish an upper limit of injection pressure. This might be well worthy of consideration in waste injection projects where a background of experience in the area and in the unique formation does not give an upper limit injection pressure. With the establishment of the base line pressure, monitoring of injection pressures then will warn of an impending fracture initiation so that this can be avoided.

Monitoring of the movement of injected fluid in the reservoir is the most difficult of all. It has been suggested that monitor wells be utilized to observe the movements of the injected fluids within the reservoir. A static monitor well may very well never show an indication of the passage of injected fluids beyond the well unless the well is in continuous operation with sufficient withdrawal to provide a pressure sink at the point to draw injected fluid into the well bore for sampling. The continual pumping of a monitor well creates a new problem in that the pumpage from the monitor well must itself be disposed of. The simplest means of disposal would be to return the pumpage to the injection well stream for injection into the host reservoir. This then requires an oversizing of surface injection facilities to accommodate this additional well stream or well streams. If a gradual dispersion of the injected ions is occurring as the injected stream displaces the indigenous water, it can be extremely difficult to identify this leading edge of injection material unless some distinctive ion is present in the monitor well effluent which can serve as a flag to identify the injected material. The operation of a monitor well with continuous pumpage can, by virtue of its pressure sink, distort the shape of the injected fluid encroachment pattern to create the illusion that the injected fluid is advanced a greater distance from the injection well than is really the case. The same rationale applies to monitor wells which are drilled in an attempt to monitor vertical movements of injected fluid as with wells drilled to the host reservoir. A further complication of monitor wells which attempt to monitor vertical movement is that the creation of the pressure sink at the monitor well in an attempt to determine if there is vertical migration of the injected fluid can in reality cause this vertical migration where it might not have occurred without the operation of the pressure sink.

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SECTION IV

CHARACTERIZATION OF WASTE

INTRODUCTION

A substance or material is referred to as toxic if it can produce damage to a living organism. Its toxicity is a measure of the amount of damage a specific quantity of the substance may cause. Hazardous, however, is usually considered in terms of involvement in a situation that is potentially damaging. Often the conditions are such that the two may be used synonymously. Waste types which can be included under these definitions are of primary concern in this report.

Wastes of all types are being injected into deep wells; coming from a wide variety of industries as well as from municipal and domestic sources. These wastes range from relatively innocuous to very highly toxic and from practically inert to explosive.

The largest users of deep-well systems are the chemical, petrochemical and pharmaceutical companies, operating about half of the wells actively injecting today. Oil refineries and natural gas plants are second, with the metals industry third. Some of the other users of waste injection wells are the food industry; the paper, pulp, and paperboard industry; the textile industry, and the sanitary service industries.

Organic and inorganic chemical waste from chemical manufacture, drugs, municipal and domestic sewage, waste from the manufacture of explosives, pesticides, fertilizers, paint pigments, and radioactive materials are some of the constituents of waste streams being injected into deep-wells. Some of the chemicals found in these waste streams are inorganic salt solutions, both mineral and organic acids, caustics, chlorinated, nitrated and oxygenated hydrocarbons, heavy metals, fluorides, and cyanides. The chemicals are liquid, gases and solids, the gases and solids being either dissolved in the liquids or simply carried along by them.

Most of the waste streams are treated to remove some of the materials contained in them, before being injected into the wells. It appears, however, that in most cases the treatment is to remove or neutralize the substances which might damage the equipment or cause plugging of the formation rather than to neutralize or remove materials which might prove hazardous to the environment if they should escape the confinement of the host reservoir.

Hazardous materials are not contained in all waste streams, but some effluent does contain chemicals which could be very harmful or even lethal if they were to escape from the well or host reservoir in high enough concentrations. Although great care is taken to ensure safe construction and operation of most wells, there is always the possibility of accident. There is some question as to whether it is advisable to inject the most hazardous wastes into deep-wells without some preinjection treatment. This is because so little is known about the waste reactions and degradability when in contact with formation water and minerals at varying temperatures and pressures.

PROBLEMS OF ANALYZING TOXIC AND HAZARDOUS WASTE EFFECTS

In determining the environmental effect of toxic and hazardous waste, there are many complications that limit the detail to which a determination can be made. Most of the problems relate directly to the availability and quality of data needed for definative answers.

Human Effects Data Limitations

Data on human effects resulting from severe exposures to hazardous or toxic substances are obtained principally from reconstruction of accident situations. A second major source of human effects information is extrapolation from experimental animal data. Both sources contain many uncertainties.

Where accidents have occurred, the recording of information from the facts surrounding the accident has frequently been so unsystematic that the possibility of missing one or more key contributing factors is always present. This makes quantification of causes and effects uncertain, and accidents involving exactly the same set of circumstances do not usually occur with enough frequency to calibrate the measurement or reconstruction errors involved. Furthermore, some facts surrounding accidents are considered proprietary and, even though originally recorded, may not be generally available.

Extrapolations from animal data do not generally suffer from lack of data. More often, the problem evolves from several sets of data, one or more of which is anomalous and thereby casts uncertainty on human extrapolations. In addition, animals respond differently to doses of toxic substances administered by different dose injection routes. Thus, the results are dependent upon whether a dose was administered orally, intraperitoneally, intramuscularly, cutaneously, or via the respiratory route. This represents no unusual difficulty for an experiment designed specifically for use in extrapolating a result to humans. However, if attempt is made to infer human effects from odd bits of animal data which have been reported in many places, the question of dose route frequently arises and cannot be answered.[1]

Ecological Impact

Much of the ecological data for plants or animals suffers, to some extent, from the same limitations as described previously for human effects data. That is, very little plant or animal data have been taken in plant or animal natural habitat as a result of accidents, and when attempted, all causes and effects are not recorded. Likewise, extrapolations from one species of plant or animal to another are uncertain because of frequent anomalies observed in the available recorded data.

Furthermore, the full impact of hazardous substances on ecological systems may not be observable in isolated data on toxic effects to specific species. Important indirect or secondary impact may occur to co-inhabitants of a habitat as a result of exposures to hazardous materials in a natural environment, as opposed to an experimental laboratory. These impacts may involve predator and prey relationships, and the entire process of natural selection. The long-term result could be new and undesirable environmental balances.[1]

Time Factors

Adverse effects may occur to all ecological populations, including humans, as a result of repeated exposures to sublethal acute dosage of toxic materials, or of continuous exposures to low-level concentrations of hazardous substances. Such exposures have produced carcinogenesis and mutagenesis in animals after extended periods of time. Similar results have not been observed in humans in equivalent times. Thus, another uncertain measure is added to the problem of animal extrapolations to humans, and the difficulty of obtaining definitive long-term cause-and-effect relationships for humans in industrial or urban environments is obvious.

Measures of persistence of hazardous substances become an important adjunct to time factors. The combination of low-level exposures and persistent agents can lead to major hazards in the form of lethal or damaging accumulations of a substance. Asbestos and mercury are perhaps the two most commonly known persistent hazards. Asbestos accumulates in humans and can lead to lung cancer after many years of low-level exposure. Mercury is known to accumulate in aquatic species and may lead to serious effects in humans through a build-up of concentrations in the food chain. There are many other compounds which persist in nature and/or accumulate in food chains. Some of these are known or suspected; others have been observed occasionally but have not been quantified.[1]

HAZARDOUS WASTE AND WASTE STREAMS

Identification

There are many substances that can create hazardous conditions, because of a dangerous property of a compound or a group of compounds composing them. The extent of the danger is dependent upon the amounts of the dangerous compound present, its dilution by inert substances, and the proximity of persons or things that may be harmed by the conditions created by the compound.

The Booz-Allen report[1] states that hazardous conditions may be created by compounds that are radioactive, explosive, corrosive, toxic, flammable, pathogenic, carcinogenic, mutagenic, or have other more exotic long-range effects when their tolerance levels are exceeded.

The safe handling of such compounds is dependent on the degree of control that can be exercised to isolate the susceptible population, remove the triggering condition, or attenuate the effect below the threshold of susceptibility.

The identification of hazardous waste streams is not simple; the existence of a dangerous substance must be shown; the concentration of this substance above the level of normal susceptibility must be provable; and actual damage to a susceptible population must have occurred. In the absence of these proofs, the violation of a specific standard must be shown.

The variety of waste streams with potential hazardous effects is nearly infinite. The producers of a single product may use materials or processes that may create hazardous conditions when their products and/or process wastes are added to those of others. If the variety of products and processes increases, the probability of creating hazardous waste effects is likely to increase.

Only a plant-by-plant and well-by-well evaluation that has the full cooperation and technical participation of the operators can establish the actual hazards that exist in all waste streams now being injected into deep-well systems.

Data shown by the Booz-Allen[1] and TRW[2] reports and the information gathered for this report shows a wide diversity of wastes among the industries using deep-well systems to inject their plant effluent. Specific identification of hazardous wastes in any waste stream or for any particular industrial group will require a research effort that is beyond the scope of this study.

Evaluation Problems

In the absence of detailed data on the characteristics of waste streams being injected into deep-wells; only crude evaluations can be made as to how hazardous they may be, as little information is published concerning the hazardous waste streams which are produced. Conjecture as to their composition and characteristics is based on the hazardous characteristics of "pure" compounds produced and used in industry, and in the commercial and household sectors.

An evaluation system that rates the effectiveness of current hazardous waste handling, treatment and disposal practices must deal with several interrelated problems:

- does a hazardous waste condition exist?
- what is the condition and how serious?
- what steps have been taken to minimize the hazards?
- how effective are these actions?
- what additional steps are necessary?

If answers to these questions can be obtained, the rating system will be able to identify the degree to which a hazard exists, and evaluate the actions needed to adequately control the handling and disposal of hazardous wastes.

The identification of wastes which create hazardous conditions is a complex task. The constant factor is the material that creates the hazardous effect. The location where the waste occurs will determine who or what is threatened and the mitigating effects of fortuitous neutralization or dilution. The key to the identification of a hazardous waste condition is the determination that a potentially hazardous material is present in the waste stream in amounts that exceed the tolerance levels of the threatened population or materials.

Analysis of the waste stream to establish its hazardous properties is rather easy for radioactive, corrosive or flammable materials, but is more difficult if the significant hazard is pathogenic or toxic.

An alternative to on-site analysis is knowledge of the characteristics of the chemical components that compose the waste stream or that may enter the waste stream. When toxic materials are present, the possibility that hazardous waste conditions exist must be assumed.

Evaluation of raw materials used in the production process, the production processes used, and the by-product materials expected, can establish a list of potential constituents of the waste streams. Comparison of such compounds with a comprehensive list of toxic materials will identify the hazardous potential of the waste stream and aid in selecting the analytical techniques which can best verify initial assumptions as to hazard potential.

Characteristics

In waste streams from chemical processing, conditions of temperature and pressure modify the physical characteristics of chemical compounds and may convert solids into liquids and gases, liquids into gases, or mixtures of liquids into solids. Side reactions of compounds may produce unwanted waste by-products. Unless the specific conditions and reactants are known, the content and condition of the waste stream is indeterminate. Compounds which are individually inert, corrosive, flammable, explosive, or toxic under normal conditions, may react with other components and become relatively less dangerous or may be converted from a nonhazardous state to one of substantial hazard.

POTENTIALLY HAZARDOUS WASTE BEING INJECTED

Based upon toxicological data, degradability, persistence, solubility in water, potential reactions, corrosiveness, and environmental effect, a tentative list of chemicals which might be considered unsafe for deep-well injection has been made. Chemicals with harmful potentials considered to be limited only to formation plugging and/or corrosion of down-hole and surface equipment are not included on the list. The problems these excluded chemicals create can usually be dealt with and solved as an integral function of the operating plan of any particular deep-well system.

Those chemicals regarded as potentially unsafe for deep-well injection are:

acrolein

arsenic and arsenic compounds

cadmium and cadmium compounds

carbon disulfide

cyanides

diazinon and other pesticides

fluorides

hydrofluoric acid

hydrocyannic acid

hexavalent chromium compounds

mercury and mercury compounds

nitrobenzene

nitrophenol

All of the chemicals listed as potentially hazardous for deep-well injection have very high human and ecological hazard ratings in the Booz-Allen reports.[1] Long storage time is necessary for all of the organic chemicals. They either do not degrade or have a long persistence time and would, therefore, pose a long-term potential hazard to underground water supplies. The actual persistence time is not generally available except for some rough estimates for a few pesticide compounds. Some of the pesticides with known long persistence times are: DDD, DDT, lindane and the polychlorocyclodienes. Dinitrocresol is one of the insecticides for which no persistence data is available. Chlordane, the organophosphorus insecticides, and those listed above are among the group not recommended for deep-well disposal by the National Working Group on Insecticides.[2]

The inorganic compounds may react to form less toxic chemicals but the toxic element or radical remains, and may be converted back to the more toxic form. An example is hydrogen cyanide being converted to a salt and then upon acidification being converted back to hydrogen cyanide. Arsenic and fluoride are lethal to all forms of life including plants. Cadmium and mercury are toxic to aquatic life. Mercury and organic mercury compounds may be converted by anaerobic microorganisms to the more toxic methyl mercury.

Except for metallic cadmium and nitrobenzene, all of the chemicals listed have sufficient water solubility properties to be dissolved in underground reservoir waters and thence transported into other zones if communication exists between the host reservoir and the other zones.

Wells Injecting Hazardous Waste

Of the 383 wells permitted, 209 were operating at the time the data were collected for this report. There were 53 of these operating wells injecting one or more of the chemicals deemed potentially hazardous for deep-well injection. Known waste chemicals being injected, and the known operating data of deep-wells are shown in Appendix D, Inventory of Deep-Wells.

Environmental Implications

Assessing the implications of injecting potentially hazardous wastes into subsurface reservoirs has been a chronic dilemma confronting industry, legislators, and regulatory agencies of government since the deep-well method of waste management began.

Inasmuch as no specific illnesses or deaths are noted and documented as resulting directly from injected hazardous waste, there can be no cause and result conclusion drawn nor a definitive statement made relating the two. Much needs to be learned of the reactive characteristics of many of the substances composing the industrial waste streams when they are subjected to highly varied and great ranges of injections and storage conditions before a definitive statement can be made as to the effects they may have. Precise periodic analysis of each waste stream is necessary to determine what the reaction may be; a generalized list of components, which is often the only available data, is insufficient.

When a great variety of potentially hazardous wastes having components in concentrations greater than those adjudged acceptable by standard ratings are injected into a subsurface reservoir, a potentially hazardous situation must be assumed to exist. However, wastes should be designated as hazardous on the basis of properties of the waste stream as an entity rather than according to the properties of individual components. Also it must be assumed, until confirmed otherwise, that only waste containing hazardous or toxic components is hazardous. Developing these assumptions, it must be concluded that these substances may (1) render unusable aquifers of potable water and salaquifers, (2) contaminate mineral deposits, (3) produce mildly toxic to lethal effects upon human and animal life, and (4) retard or completely destroy plant life.

Table 3 which appears in the assessment division of Section I is an assessment summary of operating deep-wells. The table also indicates the intraformational reaction, in terms of unfavorable and not unfavorable, to the injected waste stream. Appendix C lists the individual chemicals being injected into deep-wells as of the date of this report with their characteristics.

WASTES OF UNKNOWN HAZARD POTENTIAL BEING INJECTED

Brine

Generally, brine injected into salaquifers would not be considered hazardous. However, if it should migrate from the confining salaquifer into potable water aquifers, it could render them unfit as a source of drinking water. Brine escaping to the surface may have a deleterious effect upon aquatic and plant life. The effects usually can be reversed within a relatively short time once the brine flow is stopped. Although higher animals have a remarkable tolerance for waters with relatively high salinities, and can be maintained on these for long periods without harmful effects, they will always seek fresher water, drinking brine contaminated water only as a last resort.

More often brine contamination of fresh water aquifers will have more lasting deleterious effects than brine escaping to the surface of the ground. Once contaminated an aquifer, especially if confined, is extremely difficult to purge.

Sewage

Treated sewage usually is considered an innocuous fluid to inject into subsurface reservoirs. However, very little is known about the length of time some bacteria and virus can remain alive and dormant outside a host. Therefore, sewage injected into deep-wells should be considered a latent health problem if it leaves the confines of the host reservoir. The question of dormant virus is also noted in Appendix F Recent Microbiological Research.

VOLUME OF WASTE

In 1968, the total volume of industrial waste water discharged in the United States was in excess of 54 billion m^3 (14 trillion gallons). Only 16.2 billion m^3 (4.3 trillion gallons) of this was treated before discharge. Four major industries discharge more than half of this volume. These four groups are the primary metals industry, chemicals and allied products, paper and allied products, and petroleum and coal products. The volume of waste discharged by various industries in 1968 and the volume untreated prior to discharge was:[1]

	Total		Untreated	
Industry	Billion m^3	Trillion Gals.	Billion m^3	Trillion Gals.
Chemicals	15.8	4.2	13.2	3.5
Food	3.0	0.8	2.5	0.6
Paper	7.6	2.0	4.5	1.2
Petroleum	4.5	1.2	1.1	0.3
Primary Metals	17.4	4.6	12.1	3.2
Others	5.7	1.5	4.5	1.2

The volume of industrial waste water discharged by each EPA geographic region during the same period was:[3]

Region	Number of Establishments	Discharge Billions of m^3	 Billions of Gallons
I	711	2.1	563.1
II	958	3.4	910.4
III	1 103	11.3	2 990.5
IV	1 490	6.7	1 770.9
V	2 731	15.0	3 976.7
VI	752	10.3	2 714.4
VII	476	1.0	254.2
VIII	156	0.4	116.3
IX	654	1.6	422.1
X	371	2.1	557.4
Total	9 402	54.0	14 276.0

Of the total volume of waste water being discharged from industry, in excess of 114 000 m^3 (30 million gallons) per day is being injected into disposal wells.[4] This is in excess of 42 million m^3 (11 billion gallons) per year and represents approximately 0.08 percent of the total waste discharge. The largest number of wells is in the gulf coast area of EPA Region VI, primarily in Texas and Louisiana. Of the 209 wells operating in the United States, 57 are in Texas and 52 in Louisiana.

SECTION IV

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SECTION V

WELL INVENTORY AND CASE HISTORIES

The inventory of deep-wells used for the injection of industrial waste in the United States was updated to January 1975 for this report.

NUMBER OF WELLS

A total of 383 wells were found to have been permitted; an increase of 50 wells over the last inventory completed in 1973. Data indicate that 322 of these wells were drilled and that 209 are operating. Tables 9 and 10 show a more complete recapitulation of the number and status of the wells by EPA regions and by states.

In Texas, five wells permitted and previously uncounted were drawn into the inventory. These wells were originally multiple requests on single applications and multiple permits to drill were granted under single permit numbers. Permits for eight wells were issued on three permits; two each on two permits (TX-11, TX-112), and four on one permit (TX-4). Because of lack of specific data on their present status, these additional six wells are tentatively being carried under status unknown in the tables. One well not carried by the Oklahoma Water Resources Board was added to the Oklahoma inventory. It is OK-15 which received a drilling permit from the U. S. Department of the Interior, Osage Agency.

It is possible that there are other wells similar to these six wells just indicated, that may have been missed in this inventory as well as in previous inventories.

WELL STATUS AND DATA

More detailed information on individual wells than is summarized in Tables 9 and 10 is included in Appendix D. The Appendix is sectionalized by EPA regions, and

Table 9. PERMIT STATUS OF INJECTION WELLS

AREA	TOTAL NO. WELLS PERMITTED	PDR	PDC	PDP	PNC	PND	DAF	APP	SNA
Region II									
NEW YORK	4	1		2		1			
Region III									
PENNSYLVANIA	9			9					
WEST VIRGINIA	7	7							
Region IV									
ALABAMA	5	5							
FLORIDA	10	7				3			
KENTUCKY	3	2		1					
MISSISSIPPI	2	1				1			
NORTH CAROLINA	4			4					
TENNESSEE	4	3					1		
Region V									
ILLINOIS	8	5		1		1			1
INDIANA	13	13							
MICHIGAN	34	28		5		1			
OHIO	10	8		1			1		
Region VI									
ARKANSAS	1	1							
LOUISIANA	85	58		7	1	19			
NEW MEXICO	1	1							
OKLAHOMA	15	13	1						1
TEXAS	124	82	4	12	17	8			1
Region VII									
IOWA	1	1							
KANSAS	30	30							
Region VIII									
COLORADO	2	1		1					
WYOMING	1	1							
Region IX									
CALIFORNIA	5	5							
HAWAII	4	3				1			
NEVADA	1	1							
TOTAL	383	277	5	43	18	35	2	0	3

KEY:

PDR	Permitted, Drilled	APP	Applying For Permit
PDC	Permitted, Drilled, Cancelled	SNA	Status Unknown
PDP	Permitted, Drilled, Plugged		
PNC	Permitted, Not Drilled, Permit Cancelled		
PND	Permitted, Not Drilled		
DAP	Drilled, Applying for Permit		

Table 10. OPERATING STATUS OF INJECTION WELLS

AREA	TOTAL NO.WELLS	O	NOP	NOUP	DN	PND	PC	SNA
Region II								
NEW YORK	4	1			3			
Region III								
PENNSYLVANIA	9	0	9					
WEST VIRGINIA	7	6			1			
Region IV								
ALABAMA	5	2			3			
FLORIDA	10	4	1	1	1	3		
KENTUCKY	3	2	1					
MISSISSIPPI	2	1				1		
NORTH CAROLINA	4		1		3			
TENNESSEE	4	2		1	1			
Region V								
ILLINOIS	8	4		1	1	1		1
INDIANA	13	11		1	1			
MICHIGAN	34	21	4	3	5	1		
OHIO	10	6	1		3			
Region VI								
ARKANSAS	1	1						
LOUISIANA	85	52	8		5	19	1	
NEW MEXICO	1	1						
OKLAHOMA	15	10		1	4			
TEXAS	124	57	12	6	16	8	18	7
Region VII								
IOWA	1				1			
KANSAS	30	21		2	7			
Region VIII								
COLORADO	2		1	1				
WYOMING	1	1						
Region IX								
CALIFORNIA	5	4		1				
HAWAII	4	1			2	1		
NEVADA	1	1						
TOTAL	381	209	38	18	57	34	19	8

KEY:

O	Operating
NOP	Not Operating, Plugged
NOUP	Not Operating, Unplugged
DN	Drilled, Never Used
PND	Permitted, Not Drilled
PC	Permit Cancelled, Never Drilled
SNA	Status Unknown

states included within a given region are listed alphabetically. The waste injection wells are indexed numerically, regardless of operating status under the respective states.

The well indexing and state codes used by Warner[1] and Wapora[2] are continued in this report. It was believed that by continuing with the same indexing code it would be easier to relate the data of this inventory to those data of earlier inventories. Also, on each well inventory sheet, a note has been made identifying that particular well to its index number in an earlier inventory if there is a difference.

Updating for this inventory was done by summarising the inventory data previously published, verifying the data, when needed, with the state agency involved, and gathering new data from the proper state agency or agencies by telephone or visitation.

Much of the previous inventory data upon which assessments were to be made were found to be inadequate, particularly in Louisiana and Texas. Additional data were gathered from the regulatory agencies in these states and appear in this inventory. These additional data aided greatly in assessing the deep-well systems now operating. One particularly rewarding group of data were the spot locations of most of the wells in Texas and Louisiana, which were plotted and appear in this inventory. Much information relating to well completion and equipment could not be included because of time for preparation and the extensive drafting involved.

PROJECTED GROWTH OF DEEP-WELL SYSTEMS

Table 11 is an industrial growth index developed from published information.[3,5] This table is used as a basis to forecast the increase in the use of deep-well injection systems as a means of waste management. Table 12 forecasting the number of wells to be drilled and Table 13 forecasting the number of wells to be operating during the periods indicated until 1985. The forecast tables are based on existing State and Federal regulations relating to deep-well injection of industrial wastes and do not reflect any new policies or ideas.

Table 11. INDUSTRIAL INDEX BASED ON PREDICAST
(Index Year 1973 = 100)

SIC	Industry	1974	1975	1980	1985
	Mining				
10	Metal Mining	99	105	136	154
12	Coal	107	113	137	155
13	Oil & Gas Extraction	100	102	115	126
14	Non-Metallic	100	103	125	146
	Manufacturing				
20	Food	111	122	173	183
26	Paper	137	150	164	210
28	Chemical & Allied	121	134	156	200
29	Petroleum Refining	138	156	189	244
32	Stone & Concrete	107	114	128	184
33	Primary Metals	130	149	163	211
34	Fabricated Metals	113	120	155	208
35	Machinery - Except Elect.	121	137	170	234
36	Electronics	107	120	158	225
38	Photographics	116	126	179	242
	Transportation, Gas, & Sanitary Services				
47	Transportation Service	100	100	109	113
49	Sanitary Service	102	119	186	271
50	Wholesale Trade - Durable	102	104	113	120
55	Auto Dealers & Service	94	96	97	98
	Other				
72	Personal Services	109	121	175	246

Table 12. DRILLED INDUSTRIAL WASTE STORAGE WELLS FORECAST THROUGH 1985 BASED ON PREDICAST INDEX

SIC		Well Count 1973	Forecast Total Wells 1974	1975	1980	1985
Mining						
10	Metal Mining	2	2	2	2	3
12	Coal	1	1	1	1	1
13	Oil & Gas	17	17	17	20	31
14	Non-Metallic	5	5	5	6	7
Manufacturing						
20	Food	6	7	7	9	11
26	Paper	3	4	5	5	6
28	Chemical & Allied	131	158	176	204	262
29	Petroleum Refining	51	70	80	96	124
32	Stone & Concrete	1	1	1	1	2
33	Primary Metals	16	20	24	26	34
34	Fabricated Metals	3	3	4	5	6
35	Machinery-Except Elect.	1	1	1	2	2
36	Electronics	1	1	1	2	2
38	Photographics	3	3	4	5	7
Transportation, Gas, & Sanitary Service						
47	Transportation Service	1	1	1	1	1
49	Sanitary Service	23	25	27	43	62
50	Wholesale Trade-Durable	1	1	1	1	1
55	Auto Dealers & Service	1	1	1	1	1
Other						
72	Personal Service	1	1	1	2	2
	Total	268	322	359	432	555

Table 13. OPERATING INDUSTRIAL WASTE STORAGE WELLS FORECAST THROUGH 1985 BASED ON PREDICAST INDEX

SIC		Well Count 1973	Forecast Operating Wells 1974	1975	1980	1985
Mining						
10	Metal Mining	1	1	1	1	2
12	Coal	1	1	1	1	1
13	Oil & Gas	11	11	11	13	14
14	Non-Metallic	3	3	3	4	5
Manufacturing						
20	Food	4	5	5	6	7
26	Paper	2	3	3	3	4
28	Chemical & Allied	86	105	117	135	174
29	Petroleum Refining	33	46	53	64	82
32	Stone & Concrete	1	1	1	1	1
33	Primary Metals	11	13	16	17	23
34	Fabricated Metals	2	2	3	3	4
35	Machinery-Except Elect.	1	1	1	1	1
36	Electronics	1	1	1	1	1
38	Photographics	2	2	3	3	5
Transportation, Gas, & Sanitary Service						
47	Transportation Service	1	1	1	1	1
49	Sanitary Service	15	17	18	28	41
50	Wholesale Trade-Durable	1	1	1	1	1
55	Auto Dealers & Service	1	1	1	1	1
Other						
72	Personal Service	1	1	1	1	1
	Total	178	216	241	285	369

A recapitulation of the various industries using injection wells as a method of disposal shows the chemical industry as the largest user, with a predicted 174 operating injection wells by 1985; representing an estimated growth rate of 7.3 percent. The petroleum refining industry is second with a predicted annual growth rate of 6.2 percent, and a forecast of having 82 operating waste injection wells by 1985. The sanitary service industry is third in the number of injection wells forecast with 41, but it has the highest predicted annual growth rate with 10.8 percent.

CASE HISTORIES

Selected case histories appear in Appendix E. Most of these examples have been chosen to relate to a particular geomorphic province within an EPA region or a state in an attempt to identify successful or unsuccessful deep-well systems and the reasons as to why they have been successful or unsuccessful.

Case selection was ultimately determined by the availability of information. There are probably many other deep-well systems which may have made good studies if more information on them was available. It is often difficult to get accurate, pertinent data on problem wells even though the associated problems are in no way directly related to degradation of the environment. Two detailed and well documented case studies also appear in Appendix F with the microbiological research data. These two studies are so closely related to the research investigations that it seemed more appropriate to include them with the microbiological research material.

SECTION V

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3. Walpert, S. A., Predicast Index, Predicasts, Inc., pp 423, 1973-74.

4. U. S. Department of Commerce, U. S. Industrial Outlook 1974 (with Projections to 1980) U. S. Dept. of Comm., 385 pp, 1974.

SECTION VI

RESEARCH PROJECTS RELATED TO DEEP-WELL INJECTION OF WASTE

DEEP-WELL RESEARCH

Government Funded

One hundred and two research projects related to deep-well injection of waste have been identified. Those in the U. S. have been supported in whole or in large part by either agencies of the Federal, or State Governments; those outside the U. S. were completely government funded. Funding information was available for 52 of the 102 research projects and amounts to 4.42 million dollars. An estimate of the total government funding is 8 million dollars. The number of man years allotted to these projects could not be obtained. One additional project related to monitoring is being conducted by General Electric-TEMPO. The project is in its final stages, but no details of the findings or conclusions have been seen as of the date of this report.

The projects identified in this investigation generally may be grouped as shown below, and a summary of the research in each group is included in the text. A description of individual projects is given in Appendix G', Summary of Research Related to Deep-Wells.

Type Project	Number of Projects
Area Study	34
Microbiological	4
Chemical	22
Engineering	33
Geologic-Hydrogeologic	5

Type Project (contd)	Number of Projects (contd)
Geophysical	8
Monitoring	2
Miscellaneous	1

Area Studies -

Area studies are essential and extremely useful in determining the feasibility of deep-well injection. Most of the studies identified in this group probably can be used in conjunction with feasibility studies. The general tendency, however, for area studies is to be generalized and noncommittal. Regulatory agencies should have detailed area studies covering the region over which they have jurisdiction. These studies should define use and no use areas and limits under which the deep-well system must operate as dictated by the hydrogeologic framework. Except for unusual circumstances, the preparation of these studies should be the responsibility of the regulatory agency and the state government under which it gained its authority.

Microbiological Studies -

The three studies reviewed in this report probably represent the extent of this research thus far. This is one area where a judicious selection of additional research could aid in an understanding of waste reaction in the subsurface. Heretofore this area has been neglected, except for the work which has been done on bacteriological action in relation to waterflooding projects for secondary recovery of oil.

Chemical Studies -

The reactions of any given waste stream, or mixture of wastes, once introduced into reservoirs of unknown water and mineral composition, at highly varied temperatures and pressures are little known and poorly understood.

Most of the reactions generally shown are for pure substances rather than the mixtures usually found in waste streams and so cannot be considered as the reactions which might be expected from the waste streams.

Nine of the 22 chemical studies relate in some manner to compatibility of subsurface reservoirs and injected waste or reactions within the host reservoir. Studies of these types are extremely important in developing needed information in a sector in which most data are either incomplete or lacking. Probably less has been done with waste chemistry and waste reaction within host reservoirs than any other facet of deep-well injection. This is a high priority area for study.

Engineering (Reservoir and Geologic) Studies -

The engineering aspects of deep-well injection have been thoroughly covered in research projects and the literature to date. The results of many previous studies which have been made on oil reservoirs and aquifers may be applied directly to deep-well injection projects. The greater portion of the engineering research projects identified during this study displayed a tendency toward duplication of effort.

Several of these studies were being developed on subjects about which more knowledge was needed. There are still many questions on the subjects of the effect of fluid injection on fault and joint planes, density stratification, fracture gradient pressure problems and permeability restoration that remain to be answered. However, no recommendation for future research can be made until a complete objective evaluation of work done to the present time has been made.

Reservoir modeling is not a prerequisite to the safe operation of a deep-well system. With the variables involved in any given system, the data are essentially historical throughout most of the operating life of the well. These historical data may be gathered from the operating and monitoring records of the system. What is needed is a predictive tool that can maintain a high degree of reliability from early in the operating life of the system.

Geologic-Hydrogeologic Studies -

The geologic aspects of deep-well injection have been well covered in literature and by research projects. The controlling criteria for deep-well injection have been defined and the local geology of most potential well sites is well enough known to make a firm yes or no decision on injection. Hydrogeologic studies of salaquifers is a little studied area, with some exceptions. Study in this area could be extremely useful if it were developed toward the objective of use in the management of deep-well injection systems or for use in conjunction with waste reaction within salaquifers.

Geophysical Studies -

The use of geophysical methods for monitoring, following fluid movement, and establishing general reservoir conditions is not highly developed. Specific studies for downhole monitoring tools have the potential for worthwhile projects in this field. Some important breakthroughs in predictive monitoring will occur when methods and techniques are developed to track fluid movement, predict joint or fracture magnitude and vector, or detect cement deterioration.

Monitoring Studies -

This is an area in which little has been done, and in which much needs to be done. Fluid movement within a reservoir, fluid escaping and its movement outside the original reservoir, and vertical fluid migration are three critical areas in which monitoring could be improved. Monitoring, now, is essentially a matter of retrospect. Fot it to be fully effective, there must be a concurrence of recording with fluid movement and other dynamic forces within the system. The ultimate objective is to identify problems related to injection before they become critical and destroy the integrity of the injection system or the reservoir. If deep-well systems are to remain an acceptable part of the waste management scheme, research toward predictive monitoring should be sanctioned.

Privately Funded

Only three completely privately funded research projects related to deep-well waste injection were identified. One by the Halliburton Company of Duncan, Oklahoma, one by the Dow Chemical Company of Midland, Michigan, and one by the Standard Oil Company of Indiana (now Amoco) Research Laboratory of Tulsa, Oklahoma.

Cement Research Project -

The Halliburton project was the development of a cement, resistant to chemical waste streams for use in industrial waste injection wells.[2] The successful development of the cement helped strengthen a vulnerable area of deep-well completions. Research on cementing and cementing materials is continuing.

A summary of the man hours related to the project is not available, nor is a summary of the total dollars invested in the project. A rough estimate of the total dollar investment including field testing and other items not directly assigned is between $200,000 and $400,000.

Microbiological Research Project -

The Dow project[3,5], now in progress, is research on the bacterial decomposition of specific substances (phenol). No details, including manhours and expenditures concerning this project are available at the date of this report.

Corrosion and Water Treatment -

The Standard Oil Company project[1] although directed toward the oil industry may be applied directly to deep-well injection systems to aid in controlling corrosion; one of the major problems associated with the operation of such systems. A description of the project is shown under C-13 in Appendix G.

Research Summary

The good and bad aspects to nearly all phases of deep-well injection of industrial waste have been well covered in the literature (Appendix A) and by the research efforts to date (Appendix G). Weaknesses in knowledge and understanding appear in the areas of microbiology, chemistry, and monitoring. These areas offer possibilities for future research. The total man hours and dollar effort needed for this research cannot be stated as the state-of-the-art is not fully assessed.

Investigation of deep-well-related research by industry essentially has been nil. Those industries using deep-well injection for their effluent have adopted proven water well and oilfield techniques, and have relied upon the experience of service companies or their own expertise for the system design, construction, and operation.[1,2,5,8] Research generally is limited to solving a particular problem for a particular well when this problem begins to interfere with the operation of the well.

TREATMENT OF HAZARDOUS WASTE RESEARCH

One hundred and eighty-two research projects related to the treatment of hazardous waste have been identified. All except 14 have received government funding, U. S. or foreign. Information on the funding was available for 61 of the 182 projects and amounts to 7.55 million dollars. An estimate of the total dollar amount is 20 million dollars. Table 35 shown in Appendix H summarizes the projects.

No recommendations for additional research for waste treatment and handling can be made at this time. Over all the methods and techniques presently accepted are proven and are relatively safe. However, it is suggested that these methods be reviewed periodically to see if improvements can be made and that the methods are adequate for all conditions.

SECTION VI

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3. J. A. Leenheer, U.S.G.S. Denver, Colorado, Personal Communication, 1974.

4. J. S. Talbot, Dow Chemical Company, Houston, Texas, Personal Communication, 1974.

5. A. C. Barlow, E. I. du Pont de Nemours and Company, Wilmington, Delaware, Personal Communication, 1974.

SECTION VII

ECONOMICS OF DEEP-WELL SYSTEMS[1,2,3]

Several factors determine the economics of a deep-well system. The major factors are:

1. depth to candidate horizon
2. proposed rate of injection
3. preinjection treatment required
4. formation injectivity
5. power costs
6. labor costs
7. contract drilling costs

Each factor contributes its part to the overall economic pattern, but all factors do not have the same weight in different parts of the United States. In one part of the United States drilling costs may be low and labor costs quite high. In another part of the United States drilling costs may be high, labor costs high and some other cost factor low. Because of the diverse weighting of these economic factors and the rapidly changing prices for services and materials, relative cost factors have been developed rather than absolute costs, which would be meaningless for any situation other than the one for which they [illegible] developed. Other systems included in the economic discussion are not weighted to reflect any beneficial or detrimental effects upon the environment.

COST FACTOR COMPARISON

Figure 12 illustrates the relative cost of a well drilled in the United States as a function of depth. As an illustration, a well 2 500 feet in depth would cost one

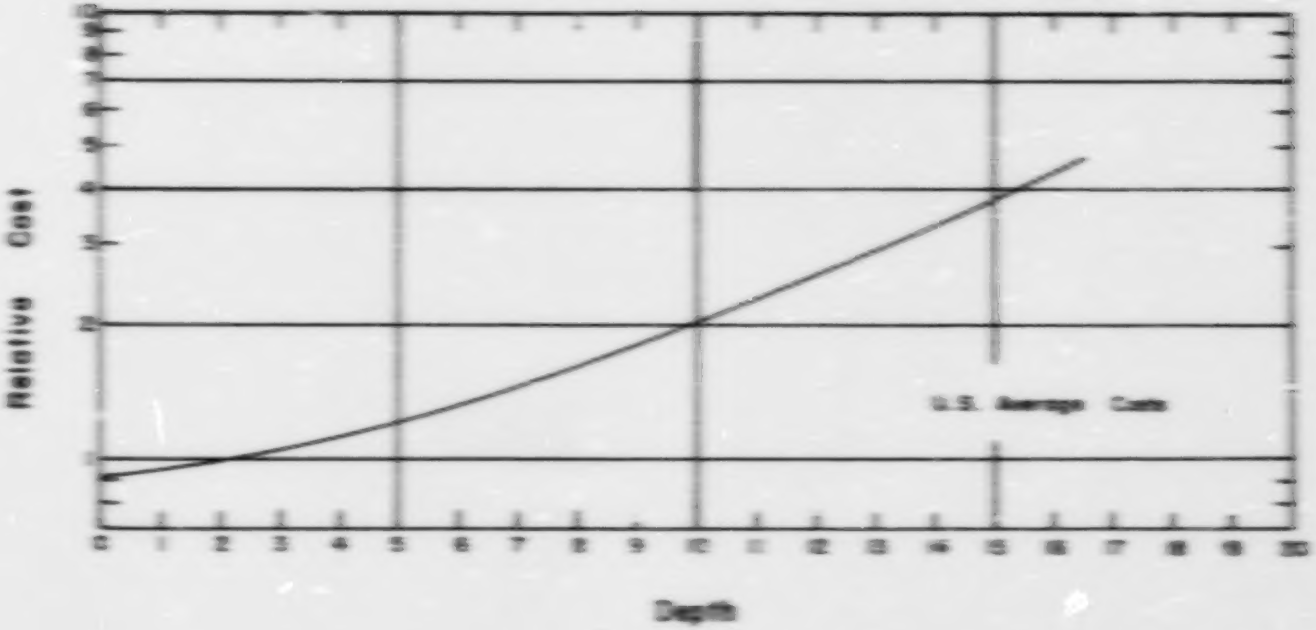

Figure 12. Average U.S. well cost

unit while a well of approximately 9,800 feet would cost 2 units. Figure 13 is a drilling cost index map of the United States. In this illustration, costs in the Appalachian basin of the eastern United States are 100 and all other regions of the United States then are related to the Appalachian basin.

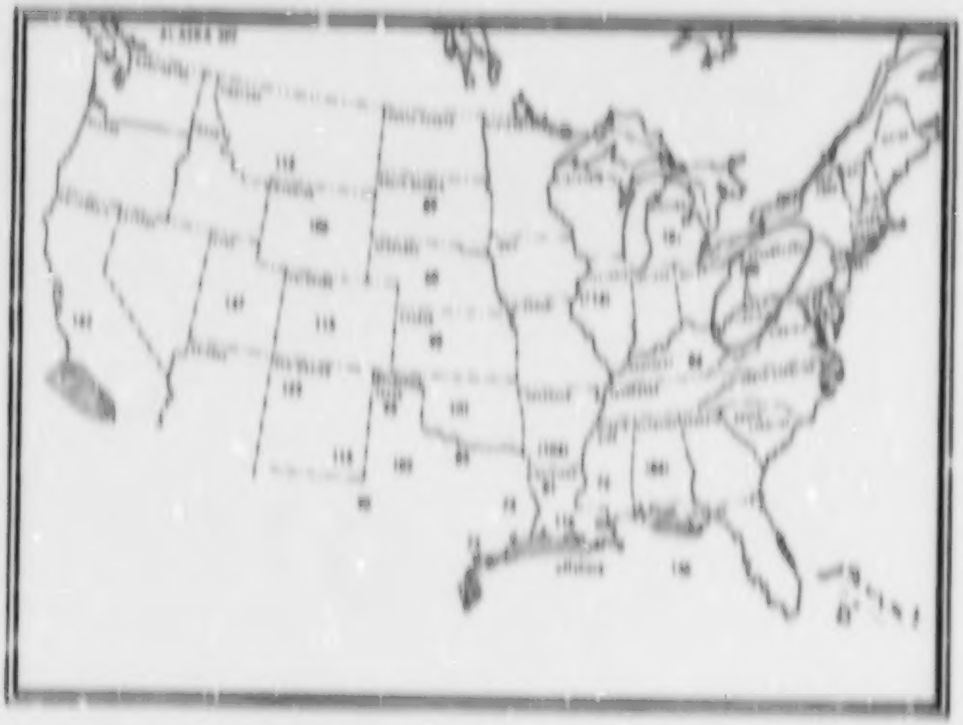

Figure 13. Relative cost index of oil & gas wells

This cost index cannot be applied without reservation because there are geological variations within states which can materially affect the drilling costs from one part of the state to another. These figures are, however, reasonable indices for first approximation purposes. Conditioning plant costs as a function of throughput are illustrated in Figure 14. There are four possible alternatives in injection plants, and these are: no treatment or filtration; filtration without treatment; treatment without filtration; and combined treatment and filtration. The required treatment will materially affect the cost of the conditioning

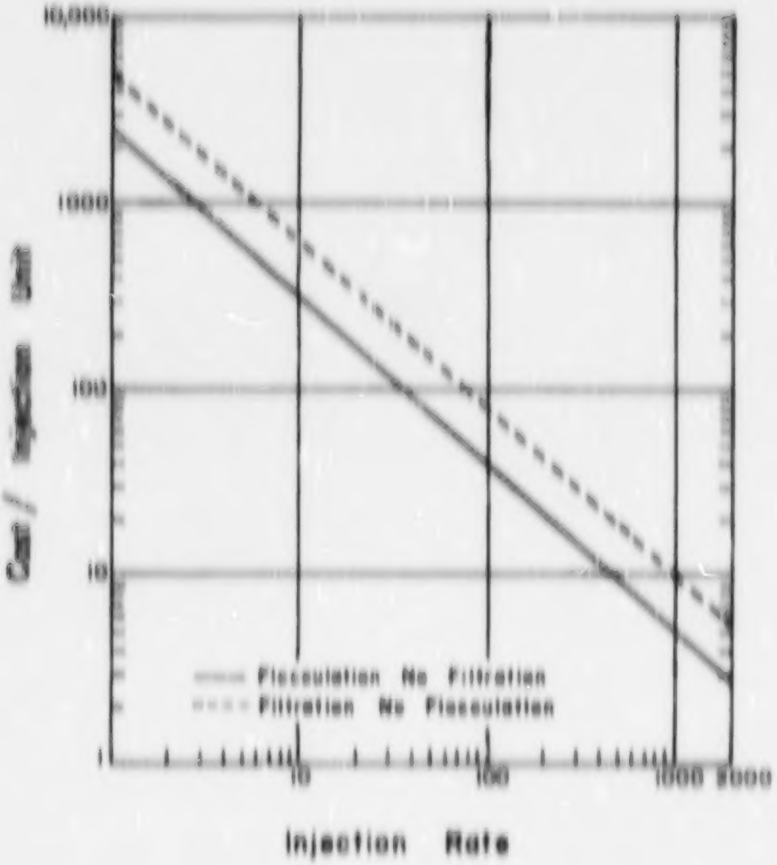

Figure 14. Relative cost for conditioning plants

plant and these cost variations with capacity are illustrated.

Relative conditioning costs as a function of injection volume are shown in Figure 13 considering filtration without flocculation and flocculation without filtration. In the lower ranges of injection there is very little difference in cost, but as the throughput increases there is considerable separation between the two illustrated modes of conditioning.

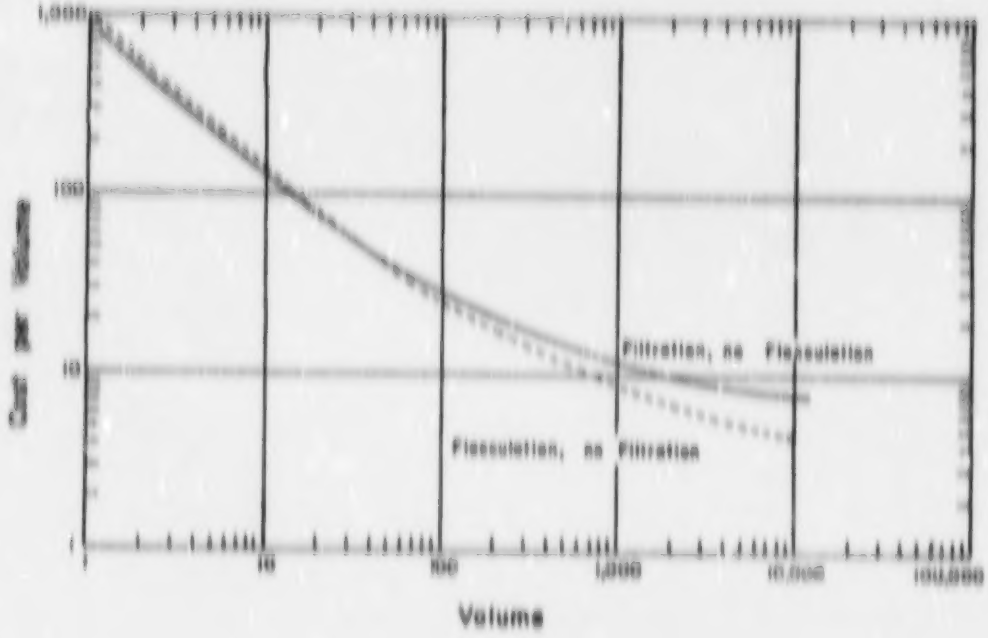

Figure 15. Relative conditioning cost

METHOD COST COMPARISON[1,2]

A comparison of deep-well injection with incineration and wet oxidation is shown in Figure 16. The cost of injection for disposal is plotted as a function of throughput for various concentrations and injection depths. In this illustration the economic superiority of deep-well systems over incineration and wet oxidation systems is clearly shown.[1]

A factor in these comparisons which has not been given adequate consideration is the cost of fuel and its availability for incineration and wet oxidation. Both of these methods require the addition of heat to sustain the process. In both wet oxidation and incineration, a concentrated liquid or solid "ash" remains after the completion of the process. Various schemes are considered for disposal of the residue and are included in the cost. However, problems associated with disposal of the residue are often of equal or greater magnitude than those of the original waste.

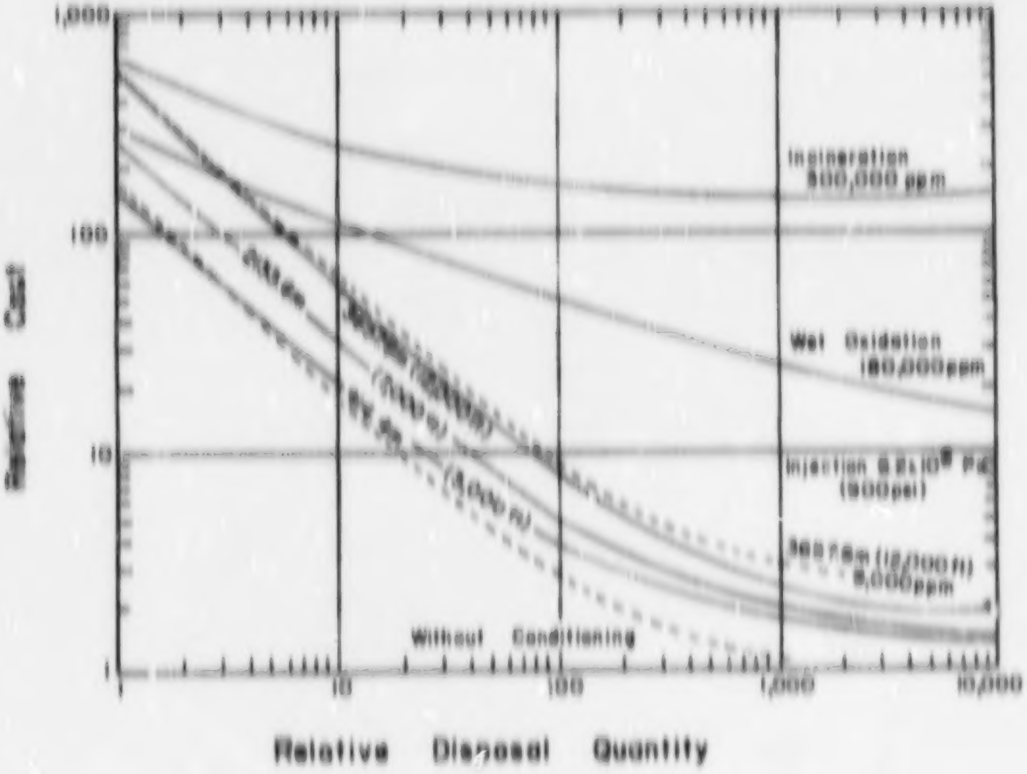

Figure 16. Unit disposal costs compared

The assumption is made for the economic analysis that an adequately isolated horizon of sufficient injection capacity exists. In an area where there is little information available concerning the candidate horizons, there is an economic hazard in proposing a deep-well system because adequate injectivity and/or isolation might not exist for it. In such a case the investment in a deep-well system will be lost and an alternate system must be used.

In areas where information is marginal, a test well probably should be drilled before a final commitment to the deep-well system is made. If the conditions are favorable, the test well can be utilized for injection and there is no loss other than the cost of the delay. If the test well proves the deep-well prospects are bad, then the loss is limited to the cost of the test well.

COST EXAMPLES

Investigations by Wright[1] in 1969, showed the economic advantages of deep-well systems over other methods of industrial waste disposal. Tables 14 and 15 show costs for the year 1969 in the Great Lakes (GL), Mid-Continent (MC), and Gulf Coast (GC) areas. Although the exact dollar figures are no longer valid, the relationship between items has remained at a relatively consistent ratio. With the application of an acceptable average yearly inflation factor, the figures presented in Tables 14 and 15 should closely approximate present costs.

Figure 17 illustrates total cost of injection for three injection pressures and three rates of injection as a function of depth.

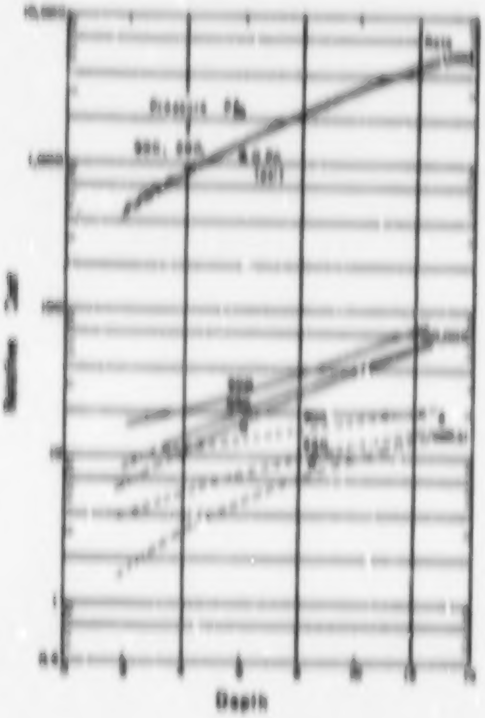

Figure 17. Cost of injection

Table 14. ECONOMIC COMPARISON OF DEEP-WELL SYSTEMS AND SURFACE TREATMENT

EPA Region	Area	Plant	Capital		Operating Cost/Year		Yearly Savings Well System
			Well System	Surface Treatment	Well System	Surface Treatment	
VI	MC	A	$125,000	$ 500,000	$ 20,000	$100,000	$ 80,000
VI	GC	B	300,000	140,000	52,000	178,000	126,000
V	GL	C	468,000	1,250,000	62,000	395,000	333,000
V	GL	D	270,000	1,500,000*	100,000	600,000	500,000

*Incineration, system cost estimated

Table 15. DEEP-WELL FACILITY AVERAGE OPERATING COST

EPA Region	Area	No. Wells*	Cum. Inj/Well m^3(Gals.) x 10^6	Inj/Well/Yr. m^3(Gals.) x 10^6	Yearly Cost Mils/m^3(Gal.)
V	GL	10	1.95 (515.9)	.236 (62.3)	111 (0.42)
VI & VII	MC	5	.776 (204.9)	.258 (68.2)	42 (0.16)
VI	GC	14	1.07 (283.2)	.261 (69.0)	309 (1.17)

*Available data

SECTION VII

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SECTION VIII

LEGAL CONSIDERATIONS

Common law constraints consist of the rights of individuals to take legal action in the event the injection operation infringes upon their legally protected interests. Encompassed here is the law of torts, which provides remedies for a variety of civil wrongs. Of primary concern in tort law is the distribution of losses between injured parties and those responsible for the injury in accordance with some concept of social justice. Tort law also provides the remedy of injunctive relief under certain conditions, but the role of the injunction is likely to be diminished in an area subject to administrative regulation.

In the case of injection wells, administrative controls are intended to prevent injury to other parties, but, in the event that injury does occur, the injured party can seek compensation under one of several tort theories, including nuisance, negligence, strict liability, and trespass. In general, nuisance encompasses actions which interfere with the enjoyment of property and is based to a large extent on the inherent nature of the objectionable activity. Negligence applies to actions causing injury as a result of failure to employ a reasonable standard of care in conducting a given activity. The concept of strict liability or liability without fault is usually associated with activities having a relatively high potential for injury even when conducted with the best of care, and serves to transfer losses automatically to the party in control of the activity without regard to actual fault. The concept of trespass is generally used to protect exclusive property rights and therefore is applicable in cases of unauthorized entry onto land (Prosser, 1971).[1,2] There is one more principle of tort law which has wide application. It is a concept developed by a Harvard professor (Keeton, 1959) known as the rule of conditional fault. The reasoning in this instance is that an activity may be desirable even though it entails the possibilities of harmful consequences and therefore it should not be labeled a tort - if the actor pays for the damage. Here we see that the tort is not in the conduct but in not paying.[2]

"Since the choice of a legal basis of action is somewhat dependent on the nature of the injury, it is necessary to give separate consideration to the types of injury that are likely to occur. The most probable detrimental consequence of injection is the contamination or destruction of natural resources. The underlying concept of deep-well disposal is confinement of the waste material to strata of low utility, but there is always some possibility of the existence of undiscovered or currently unrecognized resources within the disposal zone. And, of course, permanent confinement may not be achieved. The waste may escape into other strata by such avenues as faults, abandoned wells or other excavations, or the injection well itself. Another potential category of injection-related injury includes instability problems arising from subsurface pressure alterations or other interference with the structural integrity of underlying formations. A third area of possible application of tort law encompasses situations in which injected materials invade the underlying space of adjacent landowners without measurable injury. The principal issue in such cases is not compensation for actual damages but rather the protection of an exclusive interest in property.

"It should be noted that only a very limited number of court cases concerning damages associated with deep-well waste disposal has been decided. Most of the existing cases concern legal controversies arising from the injection of salt water for disposal purposes or in connection with secondary-recovery methods of petroleum production. These cases have addressed some of the potential problems associated with injection wells but provide no guidance with respect to others. It should be noted that law governing secondary-recovery operations is strongly influenced by public policy considerations associated with its necessity to the petroleum industry, thereby greatly reducing the transferability of such law to industrial waste-disposal operations. The injection of oil-field brines strictly for disposal purposes is somewhat distinguishable from the injection of industrial wastes because the brine is a naturally occurring substance being returned to an environment similar to that in which it originated. Recognition of this fact is contained in the FWPCA Amendments of 1972 in which oil-field brines are exempted from the definition of pollutant. These limitations on the general applicability of decisions regarding oil-field waste-disposal practices necessitate reliance on decisions in related areas in the determination of legal principles that will serve to resolve rights conflicts between individuals. The use of analogy always has certain inherent weaknesses, but more definitive law does not exist.

"There is a substantial body of law concerning the escape of deleterious substances in general that gives an indication as to how conflicts concerning pollution damages from injected wastes might be resolved. All the theories of tort liability have been invoked in pollution cases, but the majority appear to rely on nuisance and negligence."[1]

NUISANCE

"Nuisance has been a standard basis for recovery in situations involving pollution which renders a water supply unfit for use (Gulf Oil Corp. v. Hughes, 1962; Panther Coal Co. v. Looney, 1945; Masten v. Texas Co., 1927; Love v. Nashville Agricultural and Normal Institute, 1922). Since nuisance depends on the result of the defendant's actions and not on the actions themselves, the essential elements in an allegation of nuisance are proof of actual damages and the establishment of a causal connection between the activity in question and the injury. Since direct proof of a causal relationship between an alleged source of subsurface pollution and the injury is difficult to obtain, the courts will often accept proof by inference based on circumstantial evidence. Factors usually given consideration by the courts in determining causation include (1) proximity of the suspected source to the pollution, (2) the existence of other possible sources, (3) the relationship in time between the pollution and some act of the defendant, and (4) the capability of the suspected source for causing the pollution in question. The combination of factors necessary to prove causation by inference varies from case to case depending on the circumstances surrounding each situation. Contamination by the injected waste itself would likely establish a direct causal relationship, but proof of causation in injection-related pollution cases is likely to be complicated by the fact that contamination may be caused by naturally occuring fluids which migrate in response to subsurface pressure increases. The migration of resident fluids has been a significant problem in the Port Huron, Michigan, area where industrial waste injection in Ontario, Canada, was apparently the cause of seepage of salt water, oil, and natural gas from abandoned oil wells. The situation was further complicated by the international aspect of the problem, but the fact that the pollution could not be directly connected with the injected waste was significant. It was not until a chemical analysis of the seepage indicated the presence of the injected substance that the Ontario officials took affirmative action to phase out the injection operations responsible."

NEGLIGENCE

"Negligence is also a frequently utilized basis for court actions concerning pollution problems, but the person seeking relief is under an increased burden of proof in this situation. In addition to proving damages and causation, the plaintiff must prove the acts or omissions constituting the negligence. Because of the difficulties of proving negligence where the activity in question is located on property entirely within the defendant's control, some courts have accepted general proof of negligence in place of the designation of a precise negligent act (Sinclair Refining Co. v. Bennett, 1941; Texas Co. v. Giddings, 1912). Another element of proof in negligence cases is the concept of foreseeability. The principal concern here is whether the defendant could reasonably have anticipated injury as a result of his actions. The absence of a reasonable anticipation of injury in connection with lawful uses of property has been employed to deny the right of recovery for a variety of injuries, including groundwater pollution. The doctrine has been applied to such activities as the burial of animal carcasses (Long v. Louisville and Nashville R. R. Co., 1908) and the location of privies (Davis v. Atkins, 1896), but apparently not to more extensive waste disposal operations."

LIABILITY WITHOUT FAULT

"In contrast to this group of cases where the absence of negligence has shielded the defendant from liability, another group of decisions has imposed strict liability for pollution damages without regard to negligence. This doctrine of strict liability has been applied to pollution cases primarily where potentially harmful substances are brought onto property and subsequently escape, causing injury to adjacent landowners. The doctrine has been applied to the escape of salt water in several states. In some cases, the courts have imposed strict liability on the basis of a common-law concept (Berry v. Shell Petroleum Co., 1934) first enunciated in an 1865 English case (Fletcher v. Rylands, 1865), whereas in others the basis has been a statutory enactment or administrative regulation (Gulf Oil Corp. v. Alexander, 1956). This doctrine may become significant with respect to future pollution problems which may be caused by industrial waste injection. Many of the wastes involved can be described as hazardous, and the injection process may well be viewed as an unnatural use of land, for which responsibility for accidental losses should be borne by the operator even in the absence of fault. It should be noted that some 30 states have now accepted the strict liability concept in certain areas, and the number appears to be increasing (Prosser, 1971)."

TRESPASS

"Assuming that an injected waste is effectively confined to the disposal zone so that damages are not inflicted on other parties, legal confrontations are still possible where the waste crosses property boundaries and infringes upon underlying space of adjacent landowners. The likelihood of this occurrence depends on such factors as location of the injection well with respect to property boundaries, injection rates, and characteristics of the injection zone. The customary basis for an action to protect the exclusive interest in property is trespass. Although the concept of subsurface trespass has been recognized in cases involving the extraction of underlying minerals (North Jellico Coal Co. v. Helton, 1920), the courts generally have refused to uphold the trespass concept in cases involving unauthorized entry into subsurface space in the absence of injury.

"In a 1950 case decided by the Supreme Court of Oklahoma (West Edmond Salt Water Disposal Ass'n. v. Rosecrans, 1950) the plaintiff sought to enjoin injection of salt water on adjacent property and to obtain damages for alleged trespass in connection with previous infringement of subsurface property rights. The plaintiff was requesting recovery of profits accruing to the defendant because of the alleged unauthorized use of plaintiff's land; physical damages to the land, although no specific damages were set out; and punitive damages for the oppressive disregard of plaintiff's property rights. The defendant admitted liability for any actual damages resulting from the injection but denied that damages had occurred inasmuch as the injection zone was saturated with salt water prior to the initiation of injection. The court concurred with the contention of the defendant that liability should be limited to actual damages.

"Regarding the allegation of trespass, a principal consideration of the court was whether the salt water remained the property of the defendant upon its escape to the property of others. Had ownership remained with the injector, storage beneath adjoining land apparently would have constituted trespass, but the court held that ownership and control were lost upon escape and that consequently there was no trespass. In reaching this conclusion concerning the loss of possession, the court compared the salt water with natural groundwater and petroleum, which are not necessarily fixed in position beneath one proprietor's land but are subject to migration and change of ownership. The court specifically noted that the migration of the injected fluid under plaintiff's land constituted only a displacement of a similar resident fluid. The applicability of this decision to a case involving an industrial waste not closely comparable to a natural fluid may therefore be somewhat questionable. However, a key issue in the case was the absence of actual injury to the plaintiff. A change in the nature of the injected fluid may not be significant provided the waste is confined to a stratum so that no damage is produced.

"A similar decision regarding the subsurface trespass issue had been handed down by the Supreme Court of Kentucky in 1934 in a case involving the underground storage of natural gas (Hammonds v. Central Kentucky Natural Gas Co., 1934). The court in that case also held that the injector was not guilty of trespass since he lost possession of the gas once it escaped to the plaintiff's property. Although the defendant gas company in this case was not found guilty of trespass, the loss of ownership of the injected gas must have left the company with mixed emotions about the decision. Other courts (Lone Star Gas Co. v. Murchison, 1962; White v. New York State Natural Gas Corp., 1960) have since refused to follow the Kentucky court with respect to the loss-of-possession issue where natural gas is involved, and this and other aspects of such underground storage operations are now regulated by statute in many states.

"Another potentially relevant decision with regard to the right to control use of subsurface space is a 1931 New York case (Boehringer v. Montaldo, 1931). The case did not involve injection but arose from a dispute between the buyer and seller of property with regard to an undisclosed sewer line located 150 ft below the surface. The court held that the sewer was not an encumbrance on the basis of the view that a landowner's rights are restricted to a depth of "useful ownership." The concept of indefinite ownership upward and downward was rejected as an unacceptable principle of law.

"Representative of an opposing point of view is a 1936 Kentucky case (Edwards v. Lee's Administrator, 1936) which supports the right of the landowner to exercise exclusive control over subsurface space which he cannot put to use himself. The owner of land underlain by a portion of a cave was awarded damages from an adjacent owner, on whose land the entrance was located, who made commercial use of the cave. This decision was reached in spite of the fact that the plaintiff had no means of access to the cave located 360 ft beneath his land. The primary consideration appears to have been the fact that the defendant made an economic use of space theoretically owned by another, therefore incurring liability for a portion of the profits accruing from such use.

"The author of a well-known treatise on tort law (Prosser, 1971) criticizes this holding as bad law and points to the New York sewer-line case referred to previously as the more enlightened view, but it does not appear that the issue of ownership of underground space has been the subject of enough court decisions to establish a trend of opinion effectively. Of possible relevance is the fact that the concept of limiting exclusive property rights to that space which can be put to effective use has been accepted with respect to overlying space in recognition of the needs of aviation. This restriction of exclusive property rights has been necessitated by an activity generally recognized as being in the public interest. Since the feasible uses of subsurface space have been more limited, the concept of public control has not been applied to the same extent. However, expanding utilization of subsurface space for such uses as underground storage and waste disposal may require consideration of property-rights limitations in the downward direction. A restriction of ownership of subsurface space appears to be analogous to the restriction of overlying rights, provided that freedom of use of such space is generally held to be in the public interest. Although the concept of subsurface injection of wastes is given limited acceptance at present, there appears to be no general agreement that widespread use of the underground for waste disposal is in the public interest.

"In the event that the property rights of the landowner are held to encompass exclusive control over use of subsurface space, the waste injector desiring to utilize strata underlying the property of another would have to acquire rights of a nature similar to those obtained for the underground storage of natural gas. In some jurisdictions, the acquisition of a subsurface lease may have the effect of reducing the possibility of liability for accidental damages to the lessor's property resulting from injection. For example, in some states, the holder of a mineral lease is not liable for damages to the lessor without proof of specific acts of negligence, whereas strict liability is imposed for damages off the leased premises (Holbrook v. Continental Oil Co., 1955; Phoenix v. Graham, 1953)."[1]

CONDITIONAL FAULT

In explaining conditional fault, Trelease[2] poses the questions arising from the case of Vincent v. Lake Erie Transportation Co. (1910). "A steamship was unloading at Mr. Vincent's dock when a great storm came up. The captain kept his ship tightly tied to the dock, replacing ropes as they showed signs of wearing. He saved the ship, but did $500 damage to the dock. The court held that the ship owner had to pay. ....Did the captain commit a wrong? Did he intend to harm the dock? Since he had permission to dock, was he a trespasser? Was he negligent? Wouldn't any reasonable man similarly situated try to save his ship? Under the modern definition of a tort as "socially undesirable conduct", is it socially undesirable to save a ship?" Two questions are evident, should the ship owner pay and what tort has been commited?

To clarify Trelease's summary of conditional fault and changing attitudes, two additional cases must be noted. "The reasonableness of causing the harm is said to depend upon a balancing process - the act which interferes with the use and enjoyment of the land is unreasonable unless the utility of the actor's conduct outweighs the gravity of the harm (Restatement, 1939a). As usually stated by the courts, and in the old Restatement of Torts, the weighing of utility and harm made it look very much as though a big and important industry which had both economic and social desirability might do dreadful things to some poor householder as long as the total damage was small compared with the total good produced by the industry (Restatement, 1939e)....in the case of Pennsylvania Coal Co. v. Sanderson (1886), it was decided that the coal company was not liable for polluting a stream by discharging acid mine water into it, even though it ruined the stream for domestic and ornamental use and caused actual damage to the plaintiff of almost $3,000..."

Injunctions are often considered a remedy in pollution cases, but have always been regarded as something to be used only under unusual conditions, when the remedy of damages is inadequate. The process of "balancing equities" between the interest of the plaintiff and the needs of the defendant often occurs at this point.[1] Where the defendant would suffer severe hardship from having his activities stopped, and the plaintiff would suffer considerably less if he were given money for being subjected to the nuisance, the court will deny the injunction and say that the plaintiff must be satisfied with damages. In a recent New York case, Boomer v. Atlantic Cement Co. (1970), this theory was applied in a way which has caused a considerable amount of controversy in these days of arising consciousness of environmental protection. Property owners surrounding the cement plant sustained substantial damage from smoke and dust, but the plant was a multimillion-dollar industry that formed a major part of the economic base of the community. The court found that the pollution was serious and that the cement company should be encouraged to find a solution, but nevertheless held that the industry should not be enjoined. It seemed fairer to both sides to grant permanent damages, make the defendant pay the plaintiffs $185,000 for their loss of property values, and allow the industry to continue."[7]

The rule of "conditional fault" (Keeton 1959) reasons that an activity may be desirable even though it entails the possibility of harm and therefore should not be considered a tort if the actor pays for the harm. "The fault lies not in the conduct but in not paying." Referring to Vincent v. Lake Erie Transportation Co. (1910) Trelease states, "Saving the ship is desirable conduct, not tortious, but not paying for the dock is outrageous. This principle has a fairly wide application. Today we hear much of "enterprise liability", the idea that industries should pay their own way, that manufacturers of products should be strictly liable for the harms those products cause, that "no-fault insurance" should equalize the burdens of the traffic victims and spread them over the entire automobile-transportation industry. Much of the new concern for the environment is based on this idea. The economists have a wonderful phrase for it - we should "internalize the externalities"; that is, we should see that all costs of an enterprise are paid by those who receive its benefits, and not shoved off on outsiders.

"This is the true principle that seems to govern the law of underground waste disposal. The courts have been flexibly applying any and all of the tort doctrines we have discussed as long as they produce the result the court wishes to achieve, which is compensation for the injured person. When serious damage occurs, the court may use a theory of trespass, it may find that negligence was present, it may declare the activity to be a nuisance, or it may say the activity is ultrahazardous.

"When the Restatement (Second) of Torts was being drafted last year, the nuisance rules which seemingly allow the rich and strong to confiscate the property of the poor and weak came up for considerable discussion. It was argued that the courts had rarely put such a brutal rule into effect. The rule on balancing utility against harm was amended to include this statement: "The gravity of the harm, as objectively weighed..., may be found so significant that in and of itself it requires compensation, regardless of the weight of the utility of the conduct" (Restatement (Second), 1971c). The Boomer cement case and the Pennsylvania Coal Co. case were contrasted and the significant fact noted that, although the utility of both industries far outweighed the harm they did and neither was stopped, the result in the Boomer case of making the company pay was preferable.

"Both the Boomer case and the new Restatement (Second) rule are perfect illustrations of conditional fault. The cement industry is needed economically, it is socially desirable, and the court is unwilling to stop it. However, the $185,000 of property damage is a cost of producing cement, and the court says, "Pay it". The cement company thus is encouraged to use every means possible to keep the unpleasant side effects of its operation to a minimum."[7]

SUMMARY

Legal aspects of deep-well injection are still evolving. Trelease[7] summarizes his evaluation by postulating that the courts will consider deep-well injection a socially desirable activity, not per se wrong, not to be discouraged nor to be stopped, but requiring all industries using the method to bear all costs when there is a malfunction and damage or injury occurs.

SECTION VIII

REFERENCES CITED

1. Walker, W. R., and W. E. Cox, Legal and Institutional Considerations of Deep-Well Waste Disposal, 2nd Int. AAPG-USGS-IAHS Underground Waste Manage. & Artificial Recharge Symp. (New Orleans, Sept. 26-30, 1973) preprints, Vol. 2, pp 1-19, 1973.

2. Trelease, F. J., Liability for Harm from Underground Waste Disposal, Amer. Ass. Petrol. Geol. Mem. 18, pp 369-375, 1972.

SECTION IX

LEGISLATIVE AND REGULATORY CONSIDERATIONS

Governmental controls applicable to deep-well injection are increasing as the use of the method increases. Now most states with a multiple number of deep-wells either have legislated statutes regulating these systems or have rules established by some agency or agencies of the government whose authority has been designated by legislation and designed to give regulatory authority.

Waste-treatment requirements have not been as exacting for deep-well injection as for surface discharge. Critics of the method regard it as a loophole in environmental quality control while those supporting deep-well systems insist that because the waste is removed from the usable (surface) environment, less treatment is justified. Proponents also view use of underground space as an economic resource which should be utilized when other disposal methods are more costly.

The need for regulation of deep-well systems is generally recognized and accepted because of the undesirable results which may manifest themselves because of poor design or operating practices.

STATE CONTROLS[1,2]

The regulation of deep-well injection has traditionally been a responsibility of the state. The characteristics of the regulatory programs vary widely in both the acceptance of the deep-well waste injection concept and the regulations governing construction and operation of the systems. Some states accept deep-well injection as a feasible alternative or last resort for waste disposal, others are philosophically opposed to it and probably will never grant operating permits, and one state has forbidden it by statute. Those states accepting the concept of deep-well injection show great variation in the form, substance, and administrative organization for the implementation of the regulations.

A limited number of states have adopted specific disposal-well statutes (Texas Water Code, sec. 22.001 et seq; Michigan Statutes Annotated). Some states utilize legislation created for purposes other than the control of injection wells. For example, North Carolina has a water-well statue applicable to disposal wells (General Statutes of North Carolina). In Ohio, a part of oil and gas law applies to the injection of industrial wastes (Ohio Revenue Code, sec. 1509.01 et seq). A number of states regulate subsurface disposal through use of the pollution-control statute applicable to surface water.

The wording of the pollution-control statute of several states specifically encompasses disposal wells (West Virginia Code; Annotated Code of Maryland; Arizona Revised Statutes Annotated; Colorado Revised Statutes), whereas in others no explicit reference is made. Many state pollution-control laws may reasonably be interpreted to apply to disposal-well operations without specifically including them as the laws cover discharges of wastes to both surface and groundwaters. A question may arise as to whether discharge of wastes to subsurface saline waters comes within the jurisdiction of pollution-control statutes which define "pollution" in terms of actions having adverse effects on other uses, inasmuch as such waters may have no other existing uses. However, the potential contamination of usable water in other strata if the waste should migrate from the disposal zone would likely be sufficient to support the claim that injection constitutes an activity within the jurisdiction of pollution-control legislation.

The final regulatory responsibility lies with a single agency in a number of states whereas, in certain other states, the authorization procedure requires the approval of two or more agencies. The Texas Disposal Well Act vests permit-granting authority in the Water Quality Board, but the permit is conditioned on the certification by the Texas Railroad Commission that the proposed injection well will not endanger oil- and gas-bearing strata (Texas Water Code, sec. 30.015). In Ohio, issuance of an industrial waste-injection well permit by the Division of Oil and Gas requires the approval of the State Environmental Protection Agency, the State Geological Survey, and the Division of Mines if the proposed well is located in a coal-bearing township (Ohio Revised Code).

Certain elements of the actual state requirements imposed on injection-well operations are relatively uniform, but there are substantive provisions which vary considerably among the states. One such variation involves the specification of the quality parameters defining waters from which waste discharges are to be prohibited. It is generally accepted that injection should be restricted to saline aquifers, and there is agreement that waters of low salinity may be potentially useful and should be protected. However, there is considerable variation among the states as to the upper limit on concentration used to designate potentially useful saline waters. Standards established by the New York Department of Environmental Conservation classify waters having a chloride content greater than 250 mg/l or a total-dissolved-solids content of more than 1000 mg/l as saline, but saline waters containing less than 1000 mg/l chloride or less than 2000 mg/l total solids are protected (New York codes). On the other hand, the Texas Water Quality Board considers potentially beneficial all water having a total-dissolved-mineral concentration between 3000 and 10 000 mg/l (Texas Water Quality Board). Illinois also protects all water having a total-dissolved-solids content of less than 10 000 mg/l (Illinois Sanitary Water Board, 1966). The unwritten guidelines used in Alabama prohibit waste discharges into all groundwater less saline than seawater, which contains about 33 000 mg/l of dissolved solids. The determination of what quality of water to protect should logically be based on a careful evaluation of existing and projected water needs. In the absence of complete data of this type, a conservative philosophy would be expected to govern the determination, inasmuch as it involves a possibly irreversible commitment of an important natural resource.

Another substantial variation in state regulatory controls is among preliminary information requirements. Requirements of the various states include information concerning geology, topography, wells and other excavations within a specified radius (usually about 3220 m (2 mi.)), water and mineral resources, agriculture, fish and wildlife, industrial development, population densities, culture, and other factors. Whereas some states have comprehensive regulations requiring essentially the whole gamut of possible information (Colorado Department of Health, 1974), others have relatively limited requirements (West Virginia Department of Natural Resources). Some of the apparent variation is because the requirements in force often may not be incorporated in formal regulations, but it is probable that a significant part of the variation is real.

Requirements for monitoring the injection process constitute a third aspect in which state regulations differ considerably. Injection rates and pressures and the quality of injected waste must usually be monitored at the injection well, but there has been no uniformity with respect to requirements for separate monitor wells for the determination of waste migration within the disposal zone and into other strata. A consistent policy with respect to use of monitor wells has not always been applied, even within individual states--such wells are utilized in some cases and not in others. Some of the variations can be attributed to differing conditions presented by individual injection sites. For example, the close proximity of an injection well to an aquifer serving as an important source of water supply may create a need for monitor wells which does not exist in the absence of such resources. Also the presence of a fault in the vicinity of an injection well may require the installation of monitor wells to detect movement of the waste toward the fault, or may require monitoring of fresh water aquifers near the fault to determine possible leakage. The presence of active faults may also require seismic monitoring for detection of any activity resulting from the injection operation.

Although flexibility in these and other aspects of state regulatory procedures is essential to efficient operation, it is likely that a greater amount of uniformity in state control procedures would be possible and, probably, desirable. The most effective controls applicable to a given situation in one state should also be the most effective with respect to an identical or similar situation in another state. The issue of the uniformity of criteria utilized for the control of disposal wells is of special interest where interstate aquifers are involved. The existence of less restrictive requirements in one state may have the potential of negating or compromising standards in effect in another. The efforts of one state to protect brackish water of a certain salinity could be nullified if an adjacent state allowed waste injection into interstate aquifers containing such water. This and other potential problems of an interstate nature will require cooperative state action, and will be likely to necessitate greater uniformity in state regulatory procedures. Much work remains to be done with regard to standardization of controls and the accompanying considerations of the effectiveness of various controls.

FEDERAL CONTROLS[1]

Radioactive wastes have been one of the principal exceptions to state control over subsurface disposal. The disposal of such materials has been regulated by the Atomic Energy Commission (AEC) pursuant to the Atomic Energy Act of 1954 (U.S. Code Annotated, 1954). This Act preempted state control by giving AEC exclusive authority to regulate radiation hazards associated with nuclear materials. An amendment enacted in 1959 provides for agreements with the states for transfer of certain regulatory functions, but a limitation on such agreements provides for retention of AEC authority with respect to regulation of the disposal of materials which the agency determines should not be disposed of without a federal license (U.S. Code Annotated, 1959). A potential limitation on AEC authority to regulate radioactive-waste disposal arises from a governmental reorganization plan in 1970 creating the Environmental Protection Agency (EPA). This plan transferred to EPA the responsibility for establishing environmental standards with respect to radiation (U.S. Government Reorganization Plan No. 3, 1970). Exercise of this standard-setting authority would seem to impinge upon the regulation of waste disposal by AEC.

Federal influence with respect to subsurface waste injection is expanding considerably with the implementation of the Federal Water Pollution Control Act Amendments of 1972 (U.S. Code Annotated, 1972). Although the terms of the Amendments do not directly encompass disposal wells, regulations proposed by EPA for their implementation (Code of Federal Regulations, 1972) subjected certain disposal wells to federal control. Possibly of greater significance is that provisions specifying the conditions for the approval of state permit programs to be operated in place of the National Pollutant Discharge Elimination System (NPDES) establish a basis for the imposition of federal standards on state regulatory programs for disposal wells. Existence of "adequate" authority for the state to issue permits for the disposal of pollutants into wells is one of the conditions which must be met before the state permit program to regulate the discharge of pollutants into navigable water will be approved (U.S. Code Annotated, 1972, sec. 402[b][1][D]).

Title XIV - Safety to Public Water Systems, amending the Public Health Service Act, and bearing the short title of the "Safe Drinking Water Act" was passed in December 1974. Part C of this title relates directly to waste injection wells setting forth guidelines for permitting and operation and the enforcement powers granted the Administrator.

A summary of state statutes and regulations governing deep-well injection as well as the EPA Administrator's Decision Statement No. 5, and Part C of the "Safe Drinking Water Act" are included in Appendix I, Inventory of Legislation and Regulations.

The reporting parameters required by state statutes or designated state agencies are summarized in Table 18.

[illegible]

SECTION IX

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1. Walker, W. R., and W. E. Cox, *Legal and Institutional Considerations of Deep-Well Waste Disposal*, 2nd Int. AAPG-USGS-IAHS Underground Waste Manage. & Artificial Recharge Symp. (New Orleans, Sept. 26-30, 1973) preprints, Vol. 2, pp 3-19, 1973.

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SECTION X

GLOSSARY OF TERMS

A

A.P.I. = American Petroleum Institute. Founded in 1920; national oil trade association which maintains a Division of Production whose offices are in Dallas, Texas. The A.P.I. is the leading standardizing organization on oil field drilling and producing equipment, having published a great many codes covering such matters. Also has divisions of transportation, refining and marketing.

A.S.T.M. = American Society for Testing Materials. The national offices are in Philadelphia. Like the A.P.I. and the A.S.M.E., the A.S.T.M. has promulgated a great number of codes related to oil field equipment and the materials from which such equipment is manufactured.

Abandon = To cease efforts to operate a well, and to plug the bore hole and salvage all material and equipment.

Acidize = To put acid in a well to dissolve limestone in a producing zone so that passages are formed through which fluid can be transmitted to or from the well bore.

Activated Sludge = Microorganisms imbedded in gelatinous matrices feeding on organic material under aerobic conditions.

Aggradation = Build up of topographic surface by deposition of sediment.

Aliphatic = Organic chemical compounds in which the carbon atoms are linked in open chains.

Alkaline Earth Metals = Calcium, strontium, barium, radium, beryllium and magnesium.

Alkyl = A radical obtained by removal of one hydrogen from a saturated hydrocarbon. It has the general formula C_nH_{2n+1}.

Alluvial Fan = Deposit at foot of slope, effected by water movement and with gentle slope.

Alluvial Terrace - Valley surface effected by abrupt stream downcutting after period of stream aggradation.

Alluvium - Clay, silt, sand, gravel, or other rock materials transported by flowing water and deposited in comparatively recent geologic time as sorted or semi-sorted sediments in riverbeds, estuaries, flood plains, lakes, shores and in fans at the base of mountain slopes.

Alpha Particle - A helium nuclei, two neutrons and two protons bound together so as to act as one positively charged particle.

Amorphous - Noncrystalline, having no definite shape.

Analysis, Core - Laboratory examination of geological samples taken from the well bore. This examination is used to determine the capacity of the formation to contain oil and gas, the possibility of oil and gas passing through the formation, the degree of saturation of the formation with oil, gas and water, and for other purposes.

Annular Space - The space surrounding pipe suspended in the well bore. The outer wall of the annular space may be open hole or it may be string of large pipe.

Annulus - See Annular Space.

Anoxemia - A deficiency of oxygen in the blood.

Antecedent Stream - Stream course presumed to be result of persistent established drainage that continues athwart obstructional present relief.

Anticline - Major fold in rock strata wherein strata are inclined downslope on both sides from a median line or axis.

Aqueous - In water.

Aquiclude - A rock which will store water, but will not transmit significant amounts.

Aquifer - A geologic formation, group of formations, or part of a formation that is water yielding.

Aquifuge - A rock which neither transmits nor stores water.

Aquitard - A rock that will store water and transmits enough to be significant in the study of regional ground water migration but does not transmit enough water to supply individual wells.

Argyria - A discoloration of the skin caused by prolonged contact with silver compounds.

Aromatic - An organic chemical compound which contains one or more benzene rings.

Arroyo - Deep continuous channel from foot of mountain canyons to and through alluvial fans.

Artesian - The occurrence of ground water under sufficient pressure to rise above the upper surface of the aquifer.

Artesian Aquifer - An aquifer overlain by a confining bed and containing water under artesian conditions.

Artificial Recharge - The addition of water to the ground-water reservoir by activities of man.

Aryl - A radical obtained by removal of one hydrogen atom from an aromatic hydrocarbon.

Atrophy - Wasting away.

Avalanche - Rock falls from unstable steep valley divides and sides, usually accentuated by snowfall accumulation on ridge summits.

B

BOD - See Biochemical Oxygen Demand.

Back-Off - To unscrew.

Baffles - Plates which change the direction of flow of fluids.

Bailer - A long cylindrical container, fitted with a valve at its lower end, used to remove water, sand, mud and oil from a well.

Bailing - Operation of cleaning mud cuttings and other material from the bottom of the well bore with a bailer. See Bailer.

Bajada - Coalescence of alluvial fans at foot of mountain slopes; usually of much areal extent.

Ball and Seat - The main parts of the valves in a plunger-type oilwell pump.

Bar - Sand deposit, usually offshore, occurring at junction of river entry into sea.

Barchane - Sand dune with outline of lunar crescent, with windward slope at convex side and horns pointing downwind.

Base Flow - The fair-weather flow of streams, composed largely of ground-water effluent.

Bastard - Any equipment of non-standard shape or size.

Batch - A definite amount of oil, mud, acid, or other liquid in a tank or pipe line.

Bay - Elongate depressions in coastal plain, 5-10 feet deep with gentle slopes dipping into flat bottom, usually attributed to solution in interfluves.

Berm - Remnant valley shoulder after rapid down cutting by stream.

Beta Particle - Electrons emitted from radioactive atoms.

Biochemical Oxygen Demand (BOD) - The quantity of oxygen utilized primarily in the biochemical oxidation of organic matter in a specified time and at a specified temperature. The time and temperature are usually five days and 20°C.

Biological Degradation - Decomposition by bacterial action.

Black Flange (also a blind flange) - A solid disc used to dead end a companion flange.

Blank Liner - A liner without perforations.

Blank-Off - To close off, such as with a blank flange or bull plug.

Bleeder - A valve or pipe through which bleeding is done.

Bleed Off or Bleed Down - To reduce pressure slowly through a control valve.

Blow-Out - A hollow eroded into highest section of the windward side of a barchane (sand dune); usually a feature of shore dunes.

Blow-Out - A sudden, violent escape of gas and oil (and sometimes water) from a drilling well when high pressure gas is encountered and preparation to prevent or to control the escape has not been made.

Brackish Water - Water containing a concentration of total dissolved solids of 1,000-10,000 parts per million.

Bridge - An obstruction in a well, formed by intrusion of subsurface formations. A tool placed in the hole to retain cement or other material; may later be removed or drilled out, or remain permanently in place.

Brine - Water containing a concentration of total dissolved solids of over 100,000 parts per million.

Bottom Hole Contract - A contract providing for the payment of money or other consideration upon the completion of a well to a specified depth.

Bottom-Hole Pressure - The pressure at the bottom of a well.

Bottom Water - Water entering the well bore from the lower levels of a reservoir.

By-Pass - Usually refers to a pipe connection around a valve or other control mechanism. A by-pass is installed in such cases to permit passage of fluid through the line while adjustments or repairs are made on the control which is by-passed.

C

COD - See Chemical Oxygen Demand.

Cage - The part of a pump valve which holds the ball to limit its movement.

Caliper Logging - An operation to determine the diameter of the well bore or the internal diameter of casing, drill pipe or tubing. In the case of the well bore, caliper logging indicates undue enlargement of the bore due to a caving condition or other causes. In the case of tubular goods, the caliper log reveals internal corrosion.

Casing Pressure - Pressure built up between the casing and tubing.

Catalyst - A substance present in a chemical reaction, usually in small quantities, which alters the reaction without being changed itself.

Catching Samples - Geological information is obtained by studying samples of the formations penetrated by the drill. Members of the drilling crews obtain these samples from the drilling fluid as it emerges from the well bore. (Or from the bailer in case of cable tools.) This is known as catching samples. Cuttings so obtained are carefully washed until free of foreign matter and then dried and accurately labeled to show the depth at which they were found.

Cathode - The negative electrode of an electrolytic cell.

Cellar - Excavation under the derrick to provide space for items of equipment at the top of the well bore. Also serves as a pit to collect drainage of water and other fluids under the floor for subsequent disposal by jetting.

Cementing - The operation by which cement slurry is forced down through the casing and out at the lower end in such a way that it fills the space between the casing and the sides of the well bore to a predetermined height above the bottom of the well. This is for the purpose of securing the casing in place and excluding water and other fluids from the well bore.

Cementing, Squeeze - Forcing cement through perforations to seal off water or gas.

Changing Rams - On rotary drilling rigs blow-outs are prevented by the device known as the blow-out preventer. The sealing effect of the blow-out preventer is accomplished by means of parts called rams. It is necessary to change the rams when drill pipe of a different size than that previously used is put in service.

Chemical Oxygen Demand (COD) - The measure of the readily oxidizable material in water which provides an approximation of the minimum amount of organic and reducing material present.

Chemical Water Quality - The nature of water as determined by the concentration of chemical constituents.

Christmas Tree - A term applied to the valves and fittings assembled at the top of a well to control the flow of the oil.

Circulate - To cycle drilling fluid through drill pipe and well bore while drilling operations are temporarily suspended. This is done to condition the drilling fluid and the well bore before hoisting the drill pipe and to obtain cuttings from the bottom of the well bore before drilling proceeds. Circulation of the drilling fluid while drilling is suspended is usually necessary to prevent drill pipe from becoming stuck.

Circulation - Act of circulating drilling fluid to the bottom of the well and back.

Clastic - Consisting of fragments of rocks or organic structures that have been moved individually from their places of origin.

Collar - A pipe coupling threaded on the inside.

Coming Out of Hole - Withdrawing of the drill pipe from the well bore. This withdrawal is necessary to change the bit, or change from bit to core barrel, to prepare for a drill stem test, and for other reasons.

Concentration - The weight of solute dissolved in a unit volume of solution.

Conductor Pipe - A short string of casing of large diameter which is used in marshy locations and under certain other conditions. Its principal function is to keep the top of the well bore open and to provide means of conveying the up-flowing drilling fluid from the well bore to the slush pit.

Confined Water - Water separated from the atmosphere by impermeable material; also called Artesian Water.

Connate Water - Water that was deposited simultaneously with the sediments, and has not since then existed as surface water or as atmospheric moisture.

Consumptive Use - The quantity of water discharged to the atmosphere or incorporated in the products of vegetative growth or industrial processes.

Contamination - The degradation of natural water quality as a result of man's activities, to the extent that its usefulness is impaired.

Continental -

Platform - feature of earth's surface comprising that part between sea level and 3,300' elevation; the other major part is between 13,000-16,000' below sea level.

Shelf - area of shallow-water bottom between shoreline and top of relatively steep continental slope.

Slope - the descent from edge of platform to deep ocean basin; usually occurs at distant offshore and begins at average depth of 600'.

Terrace - the built-up platform that lies at the outer edge of the continental shelf in water 600' or more deep.

Contract Depth - The depth of the well bore at which the drilling contract is fulfilled.

Coring - The act of procuring a sample of the formation being drilled for geological information purposes. Coring is done by means of a core barrel. Conventional type of core barrel is put on the bottom of the drill pipe where bit normally operates. As the cutter head of the core barrel penetrates the formations a continuous sample of the formation is taken in the core barrel and later withdrawn with the drill pipe. The wire line core barrel is used in many areas since it permits coring to be done without withdrawing the drill pipe from the well bore. Instead, a core barrel is dropped inside the drill pipe and automatically locks into coring position when it reaches the bottom of the well bore.

C. P. - Point in cased hole of cementing through perforations. Also abbreviation for "casing point".

Crater (To Crater) - Term meaning "the hole is caving in". To crater refers to the results that sometimes accompany a violent blow-out during which the surface surrounding the well bore falls into a large hole blown in the earth by the force of escaping gas, oil and water. The crater sometimes covers an area of several acres and reaches a depth of several hundred feet. To crater also refers in oil field slang to any mishap which may occur to the man or the equipment.

Cut Oil - Oil that contains water; also called wet oil.

Cuttings - Particles of formation obtained from a well during drilling operation. These are washed out while circulating mud-laden fluid in rotary drilling. They are bailed out in cable tool drilling.

Crystalline - Rock composed of crystals or fragments of crystals.

Cuesta - A topographic ridge consisting of asymmetric hill slopes with one steep side into a valley and the other side gently dipped seaward.

Curie - The standard unit of radioactivity which is the quantity of a radioactive isotope which decays at 3.7 x 10^{10} disintegrations per second.

Cyanosis - A bluish discoloration of the skin, which results from insufficient oxygen in the blood.

D

D.S.T. - See Drill Stem Test.

Day Tour - See Tour.

Day Work - When a drilling contract is entered into between an operator and a drilling contractor, it is frequently composed of two parts; namely footage contract and day work. While the rig is on day work it is paid for on a daily basis at a price per day agreed upon. Day work arrangements usually cover drilling at extreme depths, coring, drill stem tests, and other operations where normal drilling operations are suspended for any reason at the request of the operator.

Decomposition - The separation of a compound into its parts.

Deflation - Removal of surficial dry alluvium by wind action; differential removal due to variable size of loose particles. Results in spectacular erosion features in desert areas.

Degradable - Capable of being decomposed, deteriorated, or decayed into simpler forms with characteristics different from the original. Also referred to as biodegradable.

Degradation of Water Quality - The act or process of reducing the level of water quality so as to impair its original usefulness.

Deliquescent - To become liquid by absorbing moisture from the air.

Demineralization - The process of reducing the concentration of chemical constituents.

Density - The weight of a substance per unit volume. For instance, the density of a drilling mud may be described as "10 lb. per gallon" or "70 lb. per cubic foot".

Depreciation - The decrease in value of any property such as a rig due to normal wear or the passing of time. By including a charge for depreciation the contractor accumulates funds to replace the rig when it is worn out.

Derrickman - The crew member whose work station is in the derrick while the tubing or rods are being hoisted or lowered into the hole. He attaches the elevators to the stands of pipe while it is being lowered into the hole and detaches the elevators while the pipe is being hoisted. Other responsibilities frequently include conditioning the drilling fluid and maintenance of the slush pumps. He is usually next in line of authority under the driller.

Desiccant - A drying agent.

Dialysis - A process by which various materials in a solution may be separated by selective diffusion through a semipermeable membrane.

Directional Drilling - While the normal well bore under usual conditions is planned to be drilled vertically, controlled directional drilling is sometimes used to drill a well at an angle from the vertical. Examples are the drilling of wells under the sea from a location on dry land and killing a blowout by means of a well drilled from a point at a safe distance from the one being brought under control. In the latter instance, the well bore drilled at an angle, permits the pumping of heavy fluids into the bore of the well which is not under control. Modern development of this technique makes possible close control on both the direction and the degree of deviation of a directional well from the vertical.

Directional Well - See Directional Drilling.

Dissolution - Dissolving or changing from a solid to a liquid state.

Disturbed Structures -

A. Youthful

Ancient Crystalline Mountain - Always rejuvenated, sometimes with monoclinal flanks.

Belted Metamorphic Mountains - Well-dissected younger mountain belts or rejuvenated ancient belts.

Domes - Singly or in complexes.

Fault Blocks - Includes troughs and hoist type mountains or ranges.

Fold Mountains - Singly or in chains.

Fold-thrust - Nappe complexes - alpine types. Mixture of sediments and crystallines.

B. Old Age - All preceeding structures are reduced to late mature or old age landscapes.

Dome - A general geomorphic term denoting a circular or oval topographic feature, usually a lifting or upwarping of a sedimentary cover caused by deep-seated igneous intrusion or by plastic flow of deep salt deposits pushed upward by differential pressure.

Domestic Well - A well which supplies water for the occupants of a single residence.

Double - A section of drill pipe casing or tubing consisting of two joints screwed together. See Thribble; Fourble.

Downcomer - A pipe through which flow is downward.

Drainage - Patterns are arrangements of spatial relationships among streams or rivers which may be influenced by inequalities of slope, rock resistance, structure and geologic history. The resultant patterns are varied and have been classed as follows:

annular - circular drainage pattern linked by one radial stream; where dome exists in alternating hard and soft sedimentary rocks.

barbed - sharp reversal in direction of stream flow as in wire hook, usually caused by capture or 'piracy' of one stream flow by another.

dendritic - random pattern of branching where no structural control is present as in homogeneous surface lithology or where surface sediments are flat lying.

deranged - uncoordinated, numerous local drainage basins and lakes, not enough time for coordination since existence of present drainage.

karst - numerous sink holes, few surface streams; caused by solution of predominant, underlying limestone causing much underground drainage.

parallel - regularly spaced parallel or sub parallel streams; usually caused by distinct slope or structural control like faults, hard rocks alongside soft rocks, and symmetrical folds.

radial - streams radiating out from a common center; associated with volcanic cones and with domes in relatively homogeneous material.

rectangular - drainage in two directions at right angles, both equally developed and caused by joint or fault control in homogeneous strata.

trellis - pattern with one dominant direction with a subsidiary direction of drainage at right angles to its link up with main stream usually associated with tilted or folded alternating hard and soft sedimentary rocks.

Drawdown - The lowering of the water table or piezometric surface caused by pumping or artesian flow.

Dresser Sleeve - A slip-type collar that is used to join plain-end pipe.

Drilling Out - This refers to drilling out of the residual cement which normally remains in the lower section of casing and the well bore after the casing has been cemented.

Drilling Under Pressure - Carrying on drilling operations while maintaining a seal at the top of the well bore to prevent the well fluids from blowing out.

Drill Stem Test - A test taken by means of special testing equipment to determine whether or not oil or gas in commercial quantities has been encountered in the well bore. This test is universally used because it yields useful information and permits the continuation of drilling after the completion of the drill stem test to explore other possible pay sections.

Driller - The employee directly in charge of a drilling rig and crew. Operation of the drilling and hoisting equipment constitute his main duties.

E

Effluent - A material which flows out.

Electrodialysis - Separation of materials in a solution by selective diffusion through a semipermeable membrane using an electric field as the driving force for the separation.

Erosion (soil) - The removal of material from the soil surface by the actions of running water, wind, or by gravity. May be thought of as 'normal' if soil formation keeps pace with soil removal and 'accelerated' or 'catastrophic' if the loss of surface material greatly exceeds that produced by weathering.

Escarpment (scarp) - A cliff or steep rock face of great linear extent; may be structurally or erosionally induced.

Estuary - That part of a lower river course that is affected by a mixing of fresh and salt water because of 'overdeepening' of the river bed to where the river bed lies below mean sea level, thereby permitting encroachment upstream by sea water.

Expansion Loop - A bend placed in a line to absorb stretch or shrinkage.

Extrusive Structures - Landforms depend on geochemistry and viscosity of magma; result in following: volcanic cones, domes, lava fields and plateaus, and calderas.

F

Fall Line - A line joining the waterfalls on a number of successive rivers that marks the point where each river descends from the upland (Piedmont) to the lowland (Coastal Plain).

Fault Block (block mountains, fault block mountains) - Mountains produced by crustal fracturing and characterized by more or less rectilinear borders, lack of continuity of formation, usually parallel or subparallel, with associated parallel and subparallel lowlands.

Faults - A movement in the earth's surface of contiguous masses wherein points of contact have been dislocated or displaced along the plane of movement.

normal - A fault wherein the acute inclined plane at the surface moves downward with respect to the masses in adjacent plane.

reverse - A fault wherein the acute inclined plane at the surface moves upward with respect to the mass in adjacent plane.

Filling the Hole - Pumping drilling fluid into the well bore as the pipe is being withdrawn in order to maintain the fluid level in the hole near the surface. The purpose is to avoid danger of blow-out and caving of the well bore.

Fishing - Operations on the rig for the purpose of retrieving from the well bore, sections of pipe, casing, or items which may have inadvertently been dropped in the hole.

Fittings - The small pipes and valves that are used to make up a system of piping.

Flood Plain - The flat ground along a stream course which is covered by water at flood stage.

Fluid Level - Distance between well head and point to which fluid rises in the well.

Fluvial Sediment - Those deposits produced by stream or river action (see Alluvium).

Formation Pressure - Pressure at the bottom of a well that is shut in.

Fourble - A section of drill pipe, casing or tubing consisting of four joints screwed together. See Double; Thribble.

Fourble Board - A platform installed in the derrick at an elevation of 80 feet to 120 feet above the derrick floor. The derrickman works on this board while the pipe is being hoisted from or lowered into the well bore.

Fracturing, Hydraulic - Forcing liquid into a formation to open passages for oil. Called also Hydrofrac, Sandfrac, Dolofrac, Stratafrac, etc., by different service companies.

Fresh Water - Water containing a concentration of total dissolved solids of 0-1,000 parts per million.

Frost Up - Icing of equipment due to the cooling effect of expanding gas.

G

gpd - Abbreviation for gallons per day.

gpm - Abbreviation for gallons per minute.

Gamma Rays - Particles of electromagnetic energy released from radioactive nuclei upon disintegration.

Gastroenteritis - Inflammation of the stomach.

Geolograph - Patented device which records the rate of penetration during drilling operations. Sometimes referred to as a "tattletale".

Geomorphic Unit (described in report) - See Disturbed Structure, Extrusive Structure, and Undisturbed Structures.

Gingivitis - Inflammation of the gums.

Glacial Drift - Boulders, till, gravel, sand or clay transported by a glacier or its meltwater.

Graben - A fault block generally elongate, that has been lowered relative to the blocks on either side without major disturbance or pronounced tilting.

Gravity, Specific - The ratio of weights of equal volume of two substances, one of which is taken as a standard. Water is taken as a standard of comparison for liquids and solids. For gas, air is usually taken, although hydrogen is sometimes used.

Griefstem - A heavy square pipe that works through the square hole in the rotary table and rotates the drill stem in rotary drilling. This is generally called the Kelly or Kelly Joint.

Ground Water - Water beneath the land surface that is under atmospheric or greater pressure - the water that enters wells and issues from springs.

Ground-Water Recharge - The processes by which water is added to a ground-water reservoir.

Ground-Water Reservoir - The earth materials and the intervening open spaces that contain ground water.

Gun-Perforating - A common method of completing a well is to set casing through the oil bearing formation and cement it at that depth. The casing is then gun-perforated by a device which is lowered in the hole and fires steel projectiles through the casing and into the pay formation.

H

Half-Life - The time required for half of the atoms in a group to decay.

Hardness - A property of water caused by the presence of calcium and magnesium, which is reflected in the use of soap and the formation of incrustations when the water is heated. It is expressed as an equivalent amount of calcium carbonate.

Hard Water - Water with over 60 mg/l of hardness. Hard water consumes more soap in the formation of a lather.

Hemolysis - The destruction of red blood cells, liberating hemoglobin.

Hole - A common term which usually refers to the well bore. Mouse Hole and Rat Hole are shallow bores under the derrick in which the kelly joint and points of drill pipe are temporarily suspended while making a connection. Rat hole also refers to hole of reduced size in the bottom of the regular well bore. Sometimes the driller "rat holes ahead" to facilitate the taking of a drill stem test when it appears that such a test will be desirable.

Horst - A fault block, generally elongate, that has been raised relative to the blocks on either side without major tilting or folding.

Hydrologic Budget - An accounting of the inflow to, outflow from, and storage in, any hydrologic unit, such as a basin, aquifer, lake, or irrigation project.

Hygroscopic - The ability of a substance to readily absorb moisture from the atmosphere.

I.A.D.C. - International Association of Drilling Contractors. Founded in 1940. National headquarters, 505 N. Ervay Street, Dallas, Texas. This organization concerns itself with research, education, accident prevention, and other matters of interest to drilling contractors. Maintains about 12 chapters throughout the United States. Official publication, The Drilling Contractor, bi-monthly magazine.

I.U.C. - International Union of Chemists.

Ice-Contact Deposits - Deposits formed in contact with melting glacier ice.

Igneous Rock - Rock formed by the solidification of molten material that originated within the earth.

Inclinometer - The trade name of an instrument used to determine whether or not the well bore is proceeding in a vertical orientation at any point. In most drilling operations either regulations of government bodies or contract stipulations, or both, provide a maximum deviation of the well bore from the vertical; commonly this maximum is three degrees. When deviation is in excess of the allowable, it is necessary to modify drilling procedure to bring it back in line.

Industrial Well - A well used for the supply of water utilized in an industrial process.

Infiltration - The flow of a liquid into soil or rock through pores or small openings.

Inhibitor - According to Webster, any agent which inhibits or prevents. In drilling and producing operations it usually refers to corrosion inhibitor. Corrosion inhibitors are used widely in drilling and producing operations to prevent corrosion of metal equipment exposed to hydrogen sulphide gas and salt water. In some drilling operations corrosion inhibitor is added to the drilling fluid to protect drill pipe.

Insulating Flange - A flange which incorporates plastic pieces to separate the metal parts.

Interfluve - Land between two rivers.

Internal-Upset - An extra-thick wall is provided on the end of drill pipe at the point where the pipe is threaded in order to compensate for the metal removed in threading. Conventional drill pipe has the extra thickness on the outside. Internal-upset drill pipe has the extra thickness on the inside with a uniform straight wall on the outside. It is usually referred to as "internal-upset, external-flush" pipe.

Ion Exchange - A reversible interchange of ions between a solid and liquid mixture. The solid is not permanently changed, but can be treated to return it to its original state.

Irrigation Return Flow - Irrigation water which is not consumed in evaporation or plant growth, and which returns to a surface stream or ground-water aquifer.

Isomers - Two or more compounds having the same molecular formulas, but different structures.

J

Jet - A hydraulic device operated by pump pressure for the purpose of cleaning fluid out of the pits and tanks on a rotary drilling location.

Jetting Out - Operation using the jet to clean out the cellar slush pit, etc.

Jet-Perforating - An operation similar to gun-perforating except that a shaped charge of high explosives is used to burn a hole through the casing instead of the gun which fires a projectile in gun-perforating.

K

Killing a Well - The act of bringing under control a well which is blowing out; also applied to the procedure of circulating water and mud into a completed well before starting well-service operations.

L

LC_{50} - Lethal concentration fifty - the concentration which would cause death to fifty percent of the exposed population when inhaled.

LD_{50} - Lethal dose fifty - the dose in milligrams per kilogram of body weight which would cause death to fifty percent of the exposed population if ingested.

Laccolith - Igneous intrusion via a conduit from a deep source that invades horizontal overlying sedimentary formations and which has lifted the sedimentary formations.

Lacustrine - Deposits which have accumulated in fresh water lakes or marshes.

Lap - Term usually applied to an interval in the cased hole where the top of a liner overlaps the bottom of a string of casing.

Lava - Generally all extruded volcanic material; more specifically that material that emerges from a vent in a fluid or pasty state.

Liner - Any string of casing whose top is situated at any point below the surface.

Location - The point at which a well is to be drilled. In Canada, the term "Wellsite" is used.

Log - A running account listing a series of events in chronological order. The driller's log is a tour-to-tour account of progress made in drilling. Electric well log is the record of geological formations which is made by a well-logging device. This device operates on the principle of differential resistance of various formations to the transmission of electric current.

Logging, Electrical - See Log.

Logging, Mud Analysis - A continuous examination of the drilling fluid circulating in the well bore for the purpose of detecting gas and other hydrocarbons.

Lose Returns - To encounter an interruption in the circulation of drilling fluid due to the fact that the fluid is entering into a porous formation underground rather than returning to the surface.

M

MAC - Maximum Allowable Concentration - The maximum concentration considered harmless to healthy adults during their working hours, assuming they breathe uncontaminated air the remaining time.

mgd - Abbreviation for million gallons per day.

mg/l - Abbreviation for milligrams per litre.

Making a Connection - The act of screwing a joint of drill pipe on to the drill stem suspended in the well bore.

Making Hole - Drilling.

Making Trip - Consists of hoisting the drill pipe to the surface and returning it to the bottom of the well bore. This is done for the purpose of changing bits, preparing to take a core, and for other reasons.

Master Gate - A large valve used to shut in a well.

Meander - A form of stream channel course that is sinuous and curved.

Metamorphic Rock - A rock which has been altered by heat or intense pressure, causing new minerals to be formed and new structure in the rock.

Metasediments - Sedimentary rocks that have been altered by metamorphic processes like heat and pressure.

Milligrams Per Litre - The weight in milligrams of any substance contained in one litre of liquid. Approximately equivalent to parts per million.

Mineralization - The natural process of accumulation of mineral elements and/or compounds in soil or water.

Miscible - Liquids being completely soluble in each other in all proportions.

Monocline - Steplike bend in otherwise horizontal or gently dipping beds; it consists of a change in the amount of dip from gentle to relatively steeper and back again to gentle, but direction of dip remains essentially unchanged.

Moraines - Characteristic glacial land forms that are the product of transport by moving ice (either mountain glaciers or continental ice sheets) and which are deposited during both the forward and backward movement of an ice front.

Mouse Hole - See Hole.

Mud-Off - In drilling, to seal the hole off from the water or oil by using mud. Applies especially to the undesirable blocking off of the flow of oil from the formation into the well bore, and special care is given to the treatment of drilling fluid to avoid this.

N

N = Abbreviation for Newton.

Nappe = Term applied to anticlinal folds that have been upset, flattened, broken, thrust forward, and finally topped by forward thrust recumbent folds from another episode.

Natural Brines = A highly saturated solution of soluble minerals, usually found in rocks associated with salt deposits or as a result of sea water evaporation.

Natural Leaching = The removal by a solvent of the more soluble minerals in soil or rocks by percolating waters.

Newton - The SI unit indicating that force which, when applied to a body having a mass of one kilogram gives it an acceleration of one metre per second per second.

Nocuous = Harmful or poisonous.

Nutrients = Compounds of nitrogen, phosphorous, and other elements essential for plant growth.

O

Offset Well = Well drilled near another one.

Open Hole = The uncased part of the well.

Operator = The person, whether proprietor or lessee, actually operating a mine or oil well or lease.

Outlier = Detached mass of rock, isolated by differential weathering along rock joints, in front of main rock body.

Outwash = Stratified glacial drift that is deposited by meltwater streams.

Outwash Fan = Mass of debris carried away by outflow stream from ice margin of glacier, especially where land slope away from margin is enough to carry such meltwater; outwash fans may be wide-spread areally.

Oxidation - The losing of electrons, the positive element going to a higher valence state.

P

Pa = Abbreviation for Pascal.

ppm - Abbreviation for parts per million.

Parts Per Million - One part per million means one part by weight of dissolved matter in a million parts by weight of solution, e.g., one kilogram of dissolved solids in one million kilograms of water or one ton of dissolved solids in one million tons of water. The measure is therefore independent of units used. Approximately equal to milligrams per litre if the concentration of dissolved solids is low and the specific gravity of the water is nearly 1.0. The relationship to milligrams per litre is shown as:

$$\text{parts per million} = \frac{\text{milligrams per litre}}{\text{specific gravity of the water}}$$

Pascal - The SI unit of pressure or stress of one newton per square metre.

Pediment - Term applied to the plains in arid and semi-arid country that exist between mountain front and low-lying terrain; the plain (pediment) has gentle slope (1-7°), smooth surface and is little dissected. The pediment surface is generally veneered bedrock and is faintly concave in longitudinal section.

Peneplain - Defined as almost featureless plain with little accordance with structure and controlled only by a close approach to base level; represents the near final stage of baselevel erosion.

Penetration, Rate of - The rate at which the drill proceeds in the deepening of the well bore. It is usually expressed in terms of feet per hour.

Perched Ground Water - An isolated body of ground water separated from the underlying main body of ground water by an unsaturated zone.

Percolation - Movement under hydrostatic pressure of water through interstices of rock or soil.

Perforate - See Gun Perforating.

Permeability - A measure of the capacity of a porous medium to transmit fluid.

Pesticides - Chemical compounds used for the control of undesirable plants, animals, or insects. The term includes insecticides, herbicides, rodent poisons, nematode poisons, and fungicides.

Persistance - The property of a chemical to remain unchanged.

Piezometric Surface - The surface defined by the levels to which water will rise in tightly cased wells. Also called potentiometric surface.

Pig - A scraping tool forced through a flow line or pipe line to clean out wax or other deposits (see rabbit).

Plateau - High plain of flatlying rocks.

Playa - Distinctive feature of desert terrain; the term playa is applied to a dry lake remnant of a former base level or erosion and may be considered to be a dry lake periodically filled with a sheet of water.

Plug Back - To seal off the bottom section of a well bore to prevent the inflow of fluid from that portion of the hole.

Pollutants - Substances that may become dissolved, suspended, absorbed or otherwise contained in water, and impair its usefulness.

Pollution - The degradation of natural water quality, as a result of man's activities, to the extent that its usefulness is impaired.

Porosity - The relative volume of the pore spaces between mineral grains in a rock as compared to the total rock volume.

Potable - Water that is drinkable.

Pressure Regulator - A valve which controls pressure in a line, downstream from the valve.

Primary Treatment (Sewage) - The removal of larger solids by screening, and of more finely divided solids by sedimentation.

Production Well - A well from which ground water is obtained.

Protection Casing - A string of casing set to protect a section of the hole and to permit drilling to continue to a greater depth. Sometimes called "protection string" and "intermediate string".

Province (Physiographic) - Any region that has unit structure, and unit geomorphic history; a stage in the hierarchical classification of regional morphologic units.

Public Supply Well - A well from which ground water is obtained serving more than one individual or household.

Pulling Casing - Removing casing from a well.

Pulling Unit - A well-service rig used in pulling rods and tubing from the well.

Pyroclastic - Literally means 'firebroken' and refers to all volcanic ejecta, large and small, that are brought to the surface from beneath via eruptive forces.

R

Rat Hole - See Hole.

Rabbit - A small plug that is run through a flow line by pressure to clean the line or test for obstructions.

Rad - Radiation absorbed dose. The absorbed dose of any nuclear radiation which is accompanied by the liberation of 100 ergs of energy per gram of absorbing material.

Radioactive Decay - The disintegration of an atom by emitting radiations.

Recharge Basin - A basin designed for the purpose of adding water to the ground-water reservoir.

Refactory- A hard to melt material used in high temperature furnaces.

Relief Valve - A valve that will open automatically when pressure gets too high.

Reverse Circulation - Normal course of drilling fluid circulation is downward inside the drill pipe and upward in the well bore space surrounding the drill pipe. On special problems, this normal circulation is sometimes reversed and the fluid returns to the surface through the drill pipe after being pumped down in the annular space.

Reverse Osmosis - The flowing of a solvent across a permeable membrane from the side of less solvent concentration to the side of higher concentration due to external pressure being applied to the side of less solvent concentration.

Rigging Up - Before the work of drilling can be started, but after the derrick has been built, tools and machinery must be installed and a supply of fuel and water must be established. This operation, which in substance is that of getting the rig ready, is conveniently described by the drillers' term "rigging up".

Riser - A pipe through which liquid travels upward.

Rock Pressure - A term used for the initial pressure of gas in a well.

Rotary Drilling - The hydraulic process of drilling consists of rotating a column of drill pipe, to the bottom of which is attached a rotary drilling bit, and during the operation, circulating through the pipe a current of mud-laden fluid, under pressure, by means of special slush pumps.

Round Trip - See Making Trip.

S

SI - Abbreviation for the International System of Units (Système International d'Unités).

Salaquifer - An aquifer containing brackish water, salt water or brine.

Salt Dome - The topographic expression of the upward push by deep salt beds that have been rendered plastic by overburden weight and may rise as much as 100 feet above the surface terrain.

Salt Water - Water containing a concentration of total dissolved solids of 10,000 - 100,000 parts per million.

Salt-Water Intrusion (or Encroachment) - Movement of salty ground water so that it replaces fresh ground water.

Sanded Up - Clogged by sand entering the well bore.

Saturation, Zone of - The zone in which interconnected interstices are saturated with water under pressure equal to or greater than atmosphere.

Schlumberger - Refers to electric well logging. It is derived from the name of a French scientist who first developed well logging. One of the leading companies in this field of operation bears this name. Around drilling rigs throughout the country it is pronounced "slumberjay".

Scree - Name applied to continuous talus slopes accumulating from debris fall from ridge summits.

Secondary Treatment - The oxidation of organic matter in sewage through bacterial action.

Sedimentary Rock - Rocks formed by the accumulation of sediment.

Set Casing - To install steel pipe or casing in a well bore. An accompanying operation is the cementing of the casing in place by surrounding it with a wall of cement extending for all or part of the depth of the well.

Shutdown - A term denoting that work has been temporarily stopped, as on an oil well.

Shut in - To close valves on a well so that it stops producing; said of a well on which the valves are closed.

Shut-in Pressure - Pressure at the top of a well when it is shut in.

Side Tracking - Drilling past a broken drill or casing which has become permanently lodged in the hole. This operation is usually accomplished by use of a special tool known as a whip-stock.

Side Wall Coring - The taking of geological samples of the formation which constitutes the wall of the well bore. Another term in general use for this operation is "side wall sampling".

Single - A joint of drill pipe. See Double, Thribble, Fourble.

Sink Hole - Any depression ranging from a shallow saucer shape to a funnel shaped or cylindrical pipe that normally give access to underground caves.

Skidding the Rig - Moving a rig from the location of a lost or completed hole preparatory to starting a new one. In skidding the rig, the move is accomplished with little or no dismantling of equipment.

Slurry - A plastic mixture of cement and water which is pumped into the well to harden, after which it supports the casing and provides a seal in the well bore to prevent migration of underground fluids.

Soft Water - Water containing 60 mg/l or less of hardness.

Solifluction - Downslope movement of soil material resulting from frost action.

Specific Capacity - The rate of discharge of water from a well divided by the drawdown of the water level in it. Properly stated, it relates to the time of pumping.

Spinner Survey - An operation designed to indicate the point at which fluids are escaping from the well bore into a cavernous or porous formation.

Spit - Subaqueous accumulation of sediment produced by longshore drift and made to extend in a straight line far out across Bay Mouth.

Spudding - Refers to the act of hoisting the drill pipe and permitting it to fall freely so that the drill bit strikes the bottom of the well bore with considerable force. This is done to clean the bit of an accumulation of sticky shale which has slowed down the rate of penetration. Careless execution of this operation can result in kinks in the drill pipe and damaged bits.

Spudding In - The very beginning of drilling operations of a well. The term had been handed down from cable tool operations in the early days of the oil industry.

Squeeze Job - Usually a secondary cementing job where cement is pumped into the formation through the bottom of the casing or through perforations to obtain a shut off of undesirable fluids.

Stomatitis - Inflammation of the mouth.

Storage (Aquifer) - The volume of water held in the interstices of the rock.

Stream (River) - Large body of flowing water, constrained in a channel.

Stuck - Refers to the drill pipe or casing inadvertently becoming fastened in the hole. May occur while drilling is in progress, while casing is being run in the hole or while the drill pipe is being hoisted. Frequently results in a fishing job.

Surface Pipe - The first string of casing to be set in a well. The length will vary in different areas from a few hundred feet to 3,000 - 4,000 feet. Some states require a minimum length to protect fresh-water sands. On some wells it is necessary to set a temporary conductor pipe which should not be confused with surface pipe as described here.

Surface Water - That portion of water that appears on the land surface.

Swab - A device that fits the inside of tubing closely that is pulled through the tubing to lift fluid from it, or to pull such a device through the tubing.

Swabbing - Operation of a lifting device to bring well fluids to the surface when the well does not flow naturally. This is a temporary operation to determine whether or not the well can be made to flow. In the event the well does not flow after being swabbed, it is necessary then to install artificial lift to bring oil to the surface.

Syncline - A downfold in strata whose opening is upward and whose flanks dip inward toward median or axis.

Synthesis - The formation of compounds from elements or other compounds.

T

T.D. - See Total Depth.

TLm - Median tolerance limit. The concentration which kills fifty percent of the test organisms.

TLV - Threshold limit valve. The concentration (mg/M^3) or dose (mg/kg of body weight) to which receptors can be exposed repeatedly without adverse effect.

Tail Out - To pull the bottom end of a pipe or sucker rod away from a well when laying down.

Temperature Survey - An operation to determine temperatures at various depths in the well bore. This survey is used in instances where there is doubt as to proper cementing of the casing, to find the location of inflows of water into the well bore, and for other reasons.

Tertiary Treatment - Advanced waste treatment which removes additional impurities which remain in the effluent after secondary treatment.

Thief Sand - A porous formation in which drilling fluid flows from the well bore during drilling operations. See Loss Returns.

Thribble - A stand of drill pipe made up of three joints each about 30 feet in length. This is equivalent to a fourble of 4 joints about 22 feet to 23 feet in length. Setting back fourbles of 30-foot joints requires a taller derrick than is normally used in rotary drilling. (See Fourble; Double.)

Total Depth (T.D.) - The greatest depth reached by a well bore.

Tour - The word which designates the shift of a drilling crew or other oil field workers is pronounced usually as if it were spelled t-o-w-e-r. The word does not refer to the derrick or tower, as some seem to think. The day tour starts at 7 or 8 in the morning. The evening tour starts at 3 or 4 o'clock in the afternoon.

Transmissivity - The rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Tubing Job - The pulling and running of tubing.

Turning to the Right - A slang term on a rotary rig referring to the drilling operation during which the drill stem is rotated in a clockwise direction.

Twist Off - To twist a joint of drill pipe in two by excessive force applied by the rotary table. Many failures which result in parting of the drill pipe in the well bore are erroneously referred to by this term. Slang for any mistake.

U

Unconfined Water - Water not separated from the atmosphere.

Unconsolidated Rocks - Uncemented or loosely coherent rocks.

Undisturbed Structures (Plains & Platforms) -

Coastal Plains - pass seaward into continental shelves with little or no break.

Lowland Plains - usually conform to structure of underlying sedimentary basins, sometimes conform to erosion surfaces discordantly crossing ancient folds.

Upland Plains - usually discordant to underlying structure; rarely conformable on existing flatlying formations.

Plateaus - horizontally bedded rocks (sediments) elevated to unusual altitudes.

Under-ream - To enlarge a drill-hole below the casing.

W

W.O.C. - See Waiting on Cement.

Waiting on Cement - After the casing has been cemented, it is necessary to suspend operations and allow time for the cement to set or harden in the well bore. The time during which operations are suspended is designated as waiting on cement.

Water Cycle - The complete cycle through which water passes; water vapor in the atmosphere, liquid and solid as precipitation as part of surface and ground water and eventually back to atmospheric vapor.

Water Quality - Pertaining to the chemical, physical and biological constituents found in water and its suitability for a particular vapor.

Water Table - That surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

Water-Table Aquifer - An aquifer containing water under water-table conditions.

Weathering - The comminution of rock strata into fine-sized particles, effected by physical or mechanical weathering (temperature, water, wind) and by chemical weathering (interaction of solvent with rock mineral and resulting changes). The latter (chemical weathering) is dependent on the presence of water.

Work-Over - To perform one or more of a variety of remedial operations on an operating well with the hope of restoring or increasing operating efficiency. Examples of work-over operations are deepening, plugging back, pulling and re-setting the liner, squeeze cementing, shooting and acidizing.